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(57) Abstract: This invention provides antibodies specific for a fullerene or derivative thereof, a single-walled fullerene nanotube, and a multi-walled fullerene nanotube, wherein the fullerene is selected from the group consisting of a fullerene carbon compound having from 20 to 540 carbon atoms. The antibodies may be monoclonal or polyclonal antibodies. This invention provides a hybridoma produced by the fusion of a mouse antibody-producing cell and a mouse myeloma which is designated 1-10F-8A and deposited with the ATCC under Accession Number PTA-279, said hybridoma producing a monoclonal antibody which binds to fullerene C60. This invention provides a mouse monoclonal antibody specific for a fullerene-C60 and produced by the mouse monoclonal antibody-producing hybridoma designated 1-10F-8A. This invention also provides methods of determining a serum concentration of a fullerene in a subject and of purifying a fullerene from a sample. This invention provides methods of preparing nonascale devices which comprise manipulating a single-walled or a multi-walled fullerene nanotube(s) with the above-described antibodies specific for single-walled or multi-walled fullerene nanotubes to assemble electronic or chemical components of the nanoscale device.

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ANTIBODIES SPECIFIC FOR FULLERENES

5        This application claims priority of U.S. Serial No. 09/386,658, filed August 31, 1999, the contents of which are incorporated by reference.

10       This invention was made with support under Grant No. HL 47377-03 from the NIH. Accordingly, the United States Government has certain rights in the invention.

15       Throughout this application, various references are referred to within parentheses. Disclosures of these publications in their entireties are hereby incorporated by reference into this application to more fully describe the state of the art to which this invention pertains. Full bibliographic citation for these references may be found at the end of this application, preceding the claims.

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## BACKGROUND OF THE INVENTION

25       The recent interest in using Buckminsterfullerene (fullerene) derivatives in biological systems raises the possibility of their assay by immunological procedures. This, in turn, leads to the question of the ability of these unprecedented polygonal structures, made up solely of carbon atoms, to induce the production of specific antibodies. Immunization of mice with a C<sub>60</sub> fullerene derivative

30       conjugated to bovine thyroglobulin yielded a population of fullerene-specific antibodies of the IgG isotype, showing that the immune repertoire was diverse enough to recognize and process fullerenes as protein conjugates. The population of antibodies included a subpopulation that crossreacted

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with a C<sub>70</sub> fullerene as determined by immune precipitation and ELISA procedures. These assays were made possible by the synthesis of water-soluble fullerene derivatives, including bovine and rabbit serum albumin conjugates and derivatives of trilylsine and pentalysine, all of which were characterized as to the extent of substitution and their UV-Vis spectra. Possible interactions of fullerenes with the combining sites of IgG are discussed based on the physical chemistry of fullerenes and previously described protein-fullerene interactions. They remain to be confirmed by the isolation of mAbs for x-ray crystallographic studies.

Until 1985 there were only two known allotropic forms of carbon: graphite and diamond. In 1985, a novel allotrope was reported in which 60 carbon atoms were arranged as a truncated icosahedron, with 60 vertices and 32 faces, 12 of which were pentagonal and 20 hexagonal (1). It was dubbed Buckminsterfullerene (usually shortened to fullerene) because of its geodesic character, a name that has held through the present day. A detailed background of metallofullerenes is provided in section B.1 of the fourth series of experiments (infra).

Considerable activity followed this discovery particularly after procedures were developed to prepare fullerenes in workable quantities (2, 3). Various fullerene-based compounds have been prepared, and diverse uses were sought for them. Some were incorporated into photovoltaic cells (4) and nanotubes (5). Others were tested for biological activity (6), including antiviral (7, 8), antioxidant (9, 10), and chemotactic activities (11), and as neuroprotective agents in a mouse model of amyotrophic lateral sclerosis (12).

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Practical application of fullerenes as biological or pharmacological agents requires that dosage and serum levels be capable of measurement, preferably by sensitive, simple immunological procedures. This, in turn, requires that specific antibodies to fullerenes be produced.

The clonal selection theory tells us that antigens elicit the production of antibodies by selecting for specific antibody producing cells already present in the repertoire of immunized animals (13). Although there is debate about the size of the "available" repertoire (14, 15), immunologists usually work on the assumption that the repertoire is diverse enough to be counted on to produce antibodies to "any" molecule a researcher may choose. This is, of course, an unreliable assumption, as experimental failures rarely find their way into the literature. The question that arises, therefore, is whether the immune repertoire is "complete" enough (15) to recognize and respond to the unprecedented geodesic structure of the fullerenes or sufficient aspects of it-more particularly, whether the immune system can process a fullerene-protein conjugate and display the processed peptides for recognition by T cells to yield IgG antibodies. We report here that it does.

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## SUMMARY OF THE INVENTION

5 This invention provides an antibody which is specific for a fullerene or derivative thereof, wherein the fullerene is selected from the group consisting of a fullerene carbon compound having from 20 to 540 carbon atoms.

10 This invention provides an antibody which is specific for a single-walled fullerene nanotube.

15 This invention provides a monoclonal antibody which is specific for a fullerene or derivative thereof, wherein the fullerene carbon compound or derivative thereof comprises a C60 fullerene, said antibody comprising an amino acid heavy chain sequence (SEQ ID NO:2) and an amino acid light chain sequence (SEQ ID NO:4).

20 This invention provides an antibody which is specific for a multi-walled fullerene nanotube.

25 This invention provides nucleic acid molecules which encode the monoclonal antibodies which are specific for a fullerene or derivative thereof, wherein the fullerene is selected from the group consisting of a fullerene carbon compound having from 20 to 540 carbon atoms.

30 This invention provides a nucleic acid molecule which encode the monoclonal antibody which is specific for a single-walled fullerene nanotube.

This invention provides a nucleic acid molecule which

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encodes the monoclonal antibody which is specific for a multi-walled fullerene nanotube.

5 This invention provides a hybridoma produced by the fusion of a mouse antibody-producing cell and a mouse myeloma, said hybridoma producing a monoclonal antibody which is specific for a fullerene.

10 This invention provides a hybridoma produced by the fusion of a mouse antibody-producing cell and a mouse myeloma which is designated 1-10F-8A and deposited with the ATCC under Accession Number PTA-279, said hybridoma producing a monoclonal antibody which binds to fullerene C60.

15 This invention provides a mouse monoclonal antibody specific for a fullerene-C60 and produced by the mouse monoclonal antibody-producing hybridoma designated 1-10F-8A and deposited with the ATCC under Accession Number PTA-279.

20 This invention provides a mouse monoclonal antibody specific for a fullerene-C60 and produced by the mouse monoclonal anti-fullereneantibody-producing hybridoma designated 1-10F-8A and deposited with the ATCC under Accession Number PTA-279, said antibody comprising a heavy chain sequence (SEQ ID  
25 NO:2) and a light chain sequence (SEQ ID NO:4).

30 This invention provides an antibody which is specific for a fullerene or derivative thereof, wherein the fullerene is selected from the group consisting of a fullerene carbon compound having from 20 to 540 carbon atoms, wherein the antibody is a polyclonal antibody.

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This invention provides a monoclonal antibody which binds to a single-walled fullerene nanotube.

5        This invention provides a monoclonal antibody which binds to a multi-walled fullerene nanotubes.

This invention provides a polyclonal antibody which binds to a single-walled fullerene nanotube.

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This invention provides a polyclonal antibody which binds to a multi-walled fullerene nanotubes.

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This invention provides an antibody specific for a fullerene, wherein the fullerene is selected from the group consisting of a fullerene carbon compound or derivative thereof comprising from 20 to 540 carbon atoms, wherein a radioactive material is encapsulated in the fullerene.

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This invention provides a method of determining a serum concentration of fullerenes in a subject which comprises: a) determining an amount of antibody which binds to the fullerene in the absence of serum; b) incubating a serum sample from a subject with an antibody which binds to the fullerene to form an antibody-fullerene complex; c) determining the amount of antibody which binds to the fullerene in the presence of serum by detecting the amount of fullerene complex; d) comparing the amount determined in step (c) with the amount determined in step (a), hereby

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determining the serum concentration of the fullerene in the subject.

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This invention provides a method of purifying a fullerene from a sample which comprises: a) preparing an affinity chromatography column to which are bound antibodies which bind to the fullerene; b) adding a sample to the affinity chromatography column so as to allow the sample to flow through the column, thereby permitting the fullerene to bind to the antibodies, thereby forming a fullerene-antibody complex on the column; and c) separating the fullerenes from the antibody-fullerene complex of step (b) by altering the pH, thereby purifying the fullerene from the sample.

This invention provides a method of preparing a nanoscale device which comprises manipulating a single-walled fullerene nanotube or nanotubes with the above-described antibody which is specific for a single-walled fullerene nanotube to assemble electronic or chemical components of the nanoscale device.

This invention provides a method of preparing a nanoscale device which comprises manipulating a multi-walled fullerene nanotube or nanotubes with the above-described antibody which is specific for a multi-walled fullerene nanotube to assemble electronic or chemical components of the nanoscale device.



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BRIEF DESCRIPTION OF THE FIGURES

Figure 1. Fullerene derivatives used in this study.

5      Figure 2. UV-Vis spectrum of 1-RSA and RSA, Both at concentrations of 100  $\mu\text{g/ml}$  in PBS.

Figure 3. UV-Vis spectrum of 1-trilysine in water (80  $\mu\text{g/ml}$ ).

10      Figure 4. ELISA study of antibody response to 1-RSA. White square, immune serum. Black diamond, preimmune serum.

15      Figure 5. Results of double diffusion in agar. Well 1, 1-TG (the immunogen); 2, 2-TG; 3, 1-BSA; 4, 1-RSA; 5, 3-RSA; and 6, TG.

20      Figure 6. ELISA inhibition experiments: Black triangle, 1-BSA; open circle, 1-(Lys)<sub>5</sub>; black circle, 1-RSA; open square, 1-TG; black square, 3-(Lys)<sub>5</sub>; x, 2-(Lys)<sub>5</sub>.

25      Figure 7A-B. 7A. Binding of the progesterone analog, 5- $\alpha$ -pregnane-20-one-3- $\beta$ -ol hemisuccinate to the Fab' fragment of a mAb specific for progesterone. This computer model was displayed in INSIGHT II from the x-ray crystal structure coordinates reported in ref. 26. Steroid is the dark cluster of spheres in the center at the top. 7B. The molecular docking of fullerene-C<sub>60</sub> by deletion of the steroid and manual docking using INSIGHT II. Fullerene is

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the sphere in the center at the top.

**Figure 8** Computer models of fullerenes  $C_{60}$  (7.2 Å) and  $C_{240}$  (~ 14 Å).  $C_{240}$  is the structure of the endcap of a [10,10] single wall nanotube.

**Figure 9** An electro microgram of micro-tubules with y-shaped MAB's bound to them along the side-walls. These fibers are grown to in-situ in response to the taxol-like MAB factors. The dimensions of micro-tubules are on the order of 25 nm, similar to multi-wall carbon nanotubes, although larger than single-wall nanotubes (SWNT).

**Figure 10** Structure of a  $C_{82}$  fullerene containing an encapsulated atom.

**Figure 11** Effect on weight gain of the fullerene derivative in Swiss mice (R.F. Schinazi et al. 1994).

**Figure 12** Measured biodistribution of  $Ho@C_{82}(OH)_x$  metallo-fullerol.

**Figure 13** Fullerene derivatives to which anti-fullerene antibodies were produced by immunization of mice with a bovine thyroglobulin (TG) conjugate of a fullerene hemisuccinate F1 containing ca. 10-12 fullerenes per TG molecule. F3 is a  $C_{70}$  derivative.

**Figure 14** Results of the double diffusion in agar experiment. Well 1 represents the F1-TG the

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immunogen; 2, the F2-TG immunogen; 3, F1-BSA conjugate; 4, F1-RSA conjugate; 5, F3-RSA conjugate; and 6 is empty.

5      **Figure 15** ELISA inhibition test results.

**Figure 16** The flow of the research studies (see infra Fourth Series of Experiments).

10      **Figure 17** a mass spectrum (MS) of a typical sublimed sample (single step at high temperature) of Holmium (Ho) containing fullerenes is shown.

15      **Figure 18** Purified Gd@C<sub>82</sub> using a single stage, anaerobic HPLC method applied to the high temperature sublimate.

20      **Figure 19** H-NMR spectrum of the hemisuccinate derivative of C<sub>80</sub>.

25      **Figure 20** Heavy chain sequence including leader of monoclonal antibody produced by mouse monoclonal anti-fullerene-hybridoma designated 1-10F-8A: 398 b.p. DNA sequence (SEQ ID NO:1) and encoded amino acid (SEQ ID NO:2).

30      **Figure 21** Light chain sequence of monoclonal antibody produced by mouse monoclonal anti-fullerene-hybridoma designated 1-10F-8A: 337 b.p. DNA sequence (SEQ ID NO:3) and encoded amino acid (SEQ ID NO:4).

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**Figure 22** During their formation nanotubes acquire caps with fullerene geometries. a rollup vector (n,m) specifies the oriented width, according the number of steps along the a and b directions. (Boris I. Yakobson and Richard E. Smalley, "Fullerene Nanotubes: C<sub>1000000</sub> and Beyond," American Scientist, 85:324 (1997), hereby incorporated by reference).

**Figure 23** 3-D crystal structure of the active site of a monoclonal antibody produced by the hybridoma produced by the fusion of a mouse antibody-producing cell and a mouse myeloma which is designated 1-10F-8A and deposited with the ATCC under Accession Number PTA-279, said hybridoma producing a monoclonal antibody which binds to fullerene C60.

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## DETAILED DESCRIPTION OF THE INVENTION

This invention provides an antibody which is specific for a fullerene or derivative thereof, wherein the fullerene is selected from the group consisting of a fullerene carbon compound having from 20 to 540 carbon atoms.

In an embodiment the above-described antibody which is specific for a fullerene or derivative thereof is a monoclonal antibody. In another embodiment of the above-described antibody which is specific for a fullerene or derivative thereof the monoclonal antibody is a monospecific monoclonal antibody. In an embodiment of the above-described antibody which is specific for a fullerene or derivative thereof, the fullerene carbon compound or derivative thereof comprises a C60 fullerene.

In another embodiment of the above-described antibody which is specific for a fullerene or derivative thereof, the fullerene carbon compound or derivative thereof comprises a C70 fullerene. In a further embodiment of the above-described antibody which is specific for a fullerene or derivative thereof, the fullerene carbon compound or derivative thereof comprises a C76 fullerene.

In another embodiment of the above-described antibody which is specific for a fullerene or derivative thereof, the fullerene carbon compound or derivative thereof comprises a C78 fullerene. In a further embodiment of the above-described antibody which is specific for a fullerene or derivative thereof, the fullerene carbon compound or derivative thereof comprises a C84 fullerene. In another

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embodiment of the above-described antibody which is specific for a fullerene or derivative thereof, the fullerene carbon compound or derivative thereof comprises a C240 fullerene.

5 This invention provides an antibody which is specific for a single-walled fullerene nanotube. a nanotube (NT) is defined by the formula "[n,m]-nanotube" wherein  $n = 0 - 500$ ,  $m = 0 - 500$ , and  $n$  and  $m$  are the same or different integers, i.e. [5,5]-NT (same), [9,0]-NT (different), but most commonly  
10 [10,10]-NT (same). One of skill may refer for a more detailed description of nanotubes, for example, to Yakobson, B.I. and Smalley, R.E., American Scientist, 85:324 (1997) which is hereby incorporated by reference.

15 This invention provides a monoclonal antibody which is specific for a fullerene or derivative thereof, wherein the fullerene carbon compound or derivative thereof comprises a C60 fullerene, said antibody comprising an amino acid heavy chain sequence (SEQ ID NO:2) and an amino acid light chain  
20 sequence (SEQ ID NO:4).

In an embodiment of the above-described antibody which is specific for a single-walled fullerene nanotube wherein the fullerene is selected from the group consisting of a  
25 fullerene or derivative thereof comprising from 20 to 540 carbon atoms, the antibody is a monoclonal antibody. In another embodiment of the above-described monoclonal antibody which is specific for a single-walled fullerene nanotube, the monoclonal antibody is a tip-specific  
30 antibody. In a further embodiment of the above-described monoclonal antibody which is specific for a single-walled fullerene nanotube, the antibody is a side-wall specific

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antibody. In yet another embodiment of the above-described monoclonal antibody which is specific for a single-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C60 fullerene.

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In a further embodiment of the above-described monoclonal antibody which is specific for a single-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C70 fullerene. In a still further

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embodiment of the above-described monoclonal antibody which is specific for a single-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C76 fullerene. In another embodiment of the above-described

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monoclonal antibody which is specific for a single-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C78 fullerene.

In yet another embodiment of the above-described monoclonal antibody which is specific for a single-walled fullerene nanotube, wherein the fullerene carbon compound or derivative thereof comprises a C84 fullerene. In a further

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embodiment of the above-described monoclonal antibody which is specific for a single-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C70 fullerene. In still another embodiment of the above-

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described monoclonal antibody which is specific for a single-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C240 fullerene.

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This invention provides an antibody which is specific for a multi-walled fullerene nanotube, wherein the fullerene is selected from the group consisting of a fullerene or

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derivative thereof comprising from 20 to 540 carbon atoms.

In an embodiment of the above-described antibody which is specific for a multi-walled fullerene nanotube wherein the fullerene is selected from the group consisting of a fullerene or derivative thereof comprising from 20 to 540 carbon atoms, the antibody is a monoclonal antibody.

In another embodiment of the above-described monoclonal antibody which is specific for a multi-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C60 fullerene.

In a further embodiment of the above-described monoclonal antibody which is specific for a multi-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C70 fullerene. In a still further embodiment of the above-described monoclonal antibody which is specific for a multi-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C76 fullerene. In another embodiment of the above-described monoclonal antibody which is specific for a multi-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C78 fullerene. In yet another embodiment of the above-described monoclonal antibody which is specific for a multi-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C82 fullerene. In a further embodiment of the above-described monoclonal antibody which is specific for a multi-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C84 fullerene. In yet another embodiment of the above-described monoclonal antibody which



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is specific for a multi-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C240 fullerene.

5 This invention provides a monoclonal antibody which binds to a single-walled fullerene nanotube, wherein the fullerene is selected from the group consisting of a fullerene or derivative thereof comprising from 20 to 540 carbon atoms.

10 This invention provides a monoclonal antibody which binds to a multi-walled fullerene nanotubes, wherein the fullerene is selected from the group consisting of a fullerene or derivative thereof comprises from 20 to 540 carbon atoms.

15 This invention provides isolated nucleic acid molecules which encode the monoclonal antibodies which are specific for a fullerene or derivative thereof, wherein the fullerene is selected from the group consisting of a fullerene carbon compound having from 20 to 540 carbon atoms.

20 This invention provides isolated nucleic acid sequences of the heavy (SEQ ID NO:1) and light chain sequences (SEQ ID NO:3) of the monoclonal antibody produced by the hybridoma produced by the fusion of a mouse antibody-producing cell and a mouse myeloma which is designated 1-10F-8A and deposited with the ATCC under Accession Number PTA-279, said hybridoma producing a monoclonal antibody which binds to fullerene C60. The encoded amino acids of the heavy chain sequence (SEQ ID NO:2) and light chain sequence (SEQ ID NO:4) of the monoclonal antibody produced by hybridoma 1-10F-8A are also provided by the invention.

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This invention provides an isolated nucleic acid molecule which encodes the monoclonal antibody which is specific for a single-walled fullerene nanotube, wherein the fullerene is selected from the group consisting of a fullerene or derivative thereof comprising from 20 to 540 carbon atoms.

This invention provides an isolated nucleic acid molecule which encodes the monoclonal antibody which is specific for a multi-walled fullerene nanotube, wherein the fullerene is selected from the group consisting of a fullerene or derivative thereof comprising from 20 to 540 carbon atoms.

In an embodiment the above-described isolated nucleic acid is DNA or RNA. In another embodiment the isolated nucleic acid is cDNA or genomic DNA. In a further embodiment the encoded antibody has substantially the same amino acid sequences of the heavy chain (SEQ ID NO:2) and light chain sequences (SEQ ID NO:4) as set forth in Figs. 20 and 21. In a still further embodiment nucleic acid encodes a human antibody. In another embodiment the above-described isolated nucleic acid has nucleic acid sequences as set forth in Figs. 20 and 21.

The DNA molecules of the subject invention also include DNA molecules coding for polypeptide analogs, fragments or derivatives of antigenic polypeptides which differ from naturally-occurring forms in terms of the identity or location of one or more amino acid residues (deletion analogs containing less than all of the residues specified for the protein, substitution analogs wherein one or more residues specified are replaced by other residues and addition analogs where in one or more amino acid residues is

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added to a terminal or medial portion of the polypeptides) and which share some or all properties of naturally-occurring forms. These molecules include: the incorporation of codons "preferred" for expression by selected non-mammalian hosts; the provision of sites for cleavage by restriction endonuclease enzymes; and the provision of additional initial, terminal or intermediate DNA sequences that facilitate construction of readily expressed vectors.

The DNA molecules described and claimed herein are useful for the information which they provide concerning the amino acid sequence of the monoclonal or polyclonal antibodies which are specific for fullerenes or derivatives thereof, wherein the fullerenes are selected from the group consisting of a fullerene carbon compound having from 20 to 540 carbon atoms, single-walled fullerene nanotubes, or multi-walled fullerene nanotubes and as products for the large scale synthesis of the polypeptides (the monoclonal or polyclonal antibodies which are specific for fullerenes or derivatives thereof or fragments thereof, single-walled fullerene nanotubes, or multi-walled fullerene nanotubes), portions which are involved in protein-protein interactions) by a variety of recombinant techniques. The molecule is useful for generating new cloning and expression vectors, transformed and transfected prokaryotic and eukaryotic host cells, and new and useful methods for cultured growth of such host cells capable of expression of the polypeptides (the monoclonal or polyclonal antibodies which are specific for fullerenes or derivatives thereof or fragments thereof, single-walled fullerene nanotubes, or multi-walled fullerene nanotubes) or portions thereof and related products.

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This invention provides a vector comprising the isolated nucleic acid which encodes a monoclonal or polyclonal antibody which is specific for fullerenes or derivatives thereof or fragments thereof, single-walled fullerene nanotubes, or multi-walled fullerene nanotubes. In an embodiment(s) the vector(s) further comprises a promoter of RNA transcription operatively linked to the nucleic acid. In another embodiment of the above-described vectors the promoter comprises a bacterial, yeast, insect or mammalian promoter. In an embodiment the vectors may further comprise a plasmid, cosmid, yeast artificial chromosome (YAC), bacteriophage or eukaryotic viral DNA.

This invention provides a host vector system for the production of a polypeptide which comprises any of the above-described vectors in a suitable host. In an embodiment of the host vector system the suitable host is a prokaryotic or eukaryotic cell. In another embodiment of the host vector system the prokaryotic cell is a bacterial cell. In a further embodiment of the host vector system the eukaryotic cell is a yeast, insect, plant or mammalian cell.

Numerous vectors for expressing the inventive proteins may be employed. Such vectors, including plasmid vectors, cosmid vectors, bacteriophage vectors and other viruses, are well known in the art. For example, one class of vectors utilizes DNA elements which are derived from animal viruses such as bovine papilloma virus, polyoma virus, adenovirus, vaccinia virus, baculovirus, retroviruses (RSV, MMTV or MoMLV), Semliki Forest virus or SV40 virus. Additionally, cells which have stably integrated the DNA into their chromosomes may be selected by introducing one or more markers which

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allow for the selection of transfected host cells. The markers may provide, for example, prototrophy to an auxotrophic host, biocide resistance or resistance to heavy metals such as copper. The selectable marker gene can be  
5 either directly linked to the DNA sequences to be expressed, or introduced into the same cell by cotransformation.

Regulatory elements required for expression include promoter sequences to bind RNA polymerase and transcription  
10 initiation sequences for ribosome binding. Additional elements may also be needed for optimal synthesis of mRNA. These additional elements may include splice signals, as well as enhancers and termination signals. For example, a bacterial expression vector includes a promoter such as the  
15 lac promoter and for transcription initiation the Shine-Dalgarno sequence and the start codon AUG. Similarly, a eukaryotic expression vector includes a heterologous or homologous promoter for RNA polymerase II, a downstream polyadenylation signal, the start codon AUG, and a  
20 termination codon for detachment of the ribosome. Such vectors may be obtained commercially or assembled from the sequences described by methods well known in the art, for example the methods described above for constructing vectors in general.

25 These vectors may be introduced into a suitable host cell to form a host vector system for producing the inventive proteins (monoclonal or polyclonal antibodies specific for fullerenes or derivatives thereof or fragments thereof,  
30 single-walled fullerene nanotubes, or multi-walled fullerene nanotubes). Methods of making host vector systems are well known to those skilled in the art.

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Suitable host cells include, but are not limited to, bacterial cells (including gram positive cells), yeast cells, fungal cells, insect cells and animal cells. Suitable animal cells include, but are not limited to HeLa cells, Cos cells, CV1 cells and various primary mammalian cells. Numerous mammalian cells may be used as hosts, including, but not limited to, the mouse fibroblast cell NIH-3T3 cells, CHO cells, HeLa cells, Ltk<sup>-</sup> cells and COS cells. Mammalian cells may be transfected by methods well known in the art such as calcium phos-phate precipitation, electroporation and microinjection.

One of ordinary skill in the art will easily obtain unique sequences from the cDNA cloned in plasmids. Such unique sequences may be used as probes to screen various mammalian cDNA libraries and genomic DNAs, e.g. mouse, rat and bovine, to obtain homologous nucleic acid sequences and to screen different cDNA tissue libraries to obtain isoforms of the obtained nucleic acid sequences. Nucleic acid probes from the cDNA cloned in plasmids may further be used to screen other human tissue cDNA libraries to obtain isoforms of the nucleic acid sequences encoding antibodies specific for fullerenes or derivatives thereof or fragments thereof, single-walled fullerene nanotubes, or multi-walled fullerene nanotubes (as well as to screen human genomic DNA to obtain the analogous nucleic acid sequences. The homologous nucleic acid sequences and isoforms may be used to produce the proteins encoded thereby.

This invention provides a method for producing a polypeptide which comprises growing any of the above-described host

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vector systems comprising the isolated nucleic acid which encodes any of the above-described polypeptides, i.e. antibodies specific for fullerenes or derivatives thereof or fragments thereof, single-walled fullerene nanotubes, or multi-walled fullerene nanotubes under suitable conditions permitting production of the polypeptide(s) and recovering the polypeptide(s) so produced.

This invention provides a method of obtaining a polypeptide, i.e. an antibody specific for fullerenes or derivatives thereof or fragments thereof, single-walled fullerene nanotubes, or multi-walled fullerene nanotubes in purified form which comprises: (a) introducing the vector comprising the isolated nucleic acid which encodes the polypeptide (antibody) into a suitable host cell; (b) culturing the resulting cell so as to produce the polypeptide; (c) recovering the polypeptide produced in step (b); and (d) purifying the polypeptide so recovered.

This invention provides a purified polypeptide which is an antibody specific for fullerenes or derivatives thereof or fragments thereof, single-walled fullerene nanotubes, or multi-walled fullerene nanotubes, wherein the fullerenes are selected from the group consisting of a fullerene carbon compound having from 20 to 540 carbon atoms. In an embodiment the above-described purified polypeptide has the amino acid sequences for the heavy and light chain sequences as set forth in Figs. 20 and 21, respectively.

This invention provides an oligonucleotide of at least 15 nucleotides capable of specifically hybridizing with a unique sequence of nucleotides present within a nucleic acid

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which encodes an antibody specific for fullerenes or derivatives thereof or fragments thereof, single-walled fullerene nanotubes, or multi-walled fullerene nanotubes, wherein the fullerenes are selected from the group consisting of a fullerene carbon compound having from 20 to 540 carbon atoms. In an embodiment of the oligonucleotide of at least 15 nucleotides capable of specifically hybridizing with a unique sequence of nucleotides present within a nucleic acid which encodes an antibody specific for fullerenes, single-walled fullerene nanotubes, or multi-walled fullerene nanotubes, the isolated nucleic acids which encodes the antibody specific for fullerenes have the nucleic acid sequences for the heavy and light chain sequences as set forth in Figs. 20 and 21, respectively. In further embodiments of any of the above-described oligonucleotides the nucleic acid may be DNA or RNA.

This invention provides a nucleic acid having a sequence complementary to the sequence of the isolated nucleic acid which encodes an antibody which is specific for a fullerene, a single-walled fullerene nanotube, or a multi-walled fullerene nanotube, wherein the fullerene is selected from the group consisting of a fullerene or derivative thereof comprising from 20 to 540 carbon atoms, and wherein the antibody is a monoclonal antibody or a polyclonal antibody.

This invention provides a hybridoma produced by the fusion of a mouse antibody-producing cell and a mouse myeloma, said hybridoma producing a monoclonal antibody which is specific for a fullerene.

This invention provides a hybridoma produced by the fusion



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of a mouse antibody-producing cell and a mouse myeloma which is designated 1-10F-8A and deposited with the ATCC under Accession Number PTA-279, said hybridoma producing a monoclonal antibody which binds to fullerene C60.

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a mouse monoclonal anti-fullerene-hybridoma produced by the fusion of a mouse antibody-producing cell and a mouse myeloma which is designated 1-10F-8A was deposited on June 25, 1999 with the American Type Culture Collection (ATCC), 10801 University Blvd., Manassas, VA 20110-2209, U.S.A. under the provisions of the Budapest Treaty for the International Recognition of the Deposit of Microorganisms for the Purposes of Patent Procedure. Mouse monoclonal anti-fullerene-hybridoma 1-10F-8A was accorded ATCC Accession Number PTA-279.

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This invention provides a mouse monoclonal antibody specific for a fullerene-C60 and produced by the mouse monoclonal antibody-producing hybridoma designated 1-10F-8A and deposited with the ATCC under Accession Number PTA-279.

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This invention provides an antibody which is specific for a fullerene or derivative thereof, wherein the fullerene is selected from the group consisting of a fullerene carbon compound having from 20 to 540 carbon atoms, wherein the antibody is a polyclonal antibody.

25

In an embodiment of the above-described polyclonal antibody which is specific for a multi-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C60 fullerene. In another embodiment of the above-described polyclonal antibody which is specific for a multi-walled

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fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C70 fullerene. In yet another embodiment of the above-described polyclonal antibody which is specific for a multi-walled fullerene nanotube, the  
5 fullerene carbon compound or derivative thereof comprises a C76 fullerene. In a further embodiment of the above-described polyclonal antibody which is specific for a multi-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C78 fullerene. In another  
10 embodiment of the above-described polyclonal antibody which is specific for a multi-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C82 fullerene. In a further embodiment of the above-described polyclonal antibody which is specific for a multi-walled fullerene nanotube, the fullerene carbon compound or derivative thereof comprises a C84 fullerene.

In a still further embodiment of the above-described polyclonal antibody which is specific for a multi-walled fullerene nanotube, the fullerene carbon compound or  
20 derivative thereof comprises a C240 fullerene.

This invention provides a polyclonal antibody which binds to a single-walled fullerene nanotube, wherein the fullerene is selected from the group consisting of a fullerene or  
25 derivative thereof comprising from 20 to 540 carbon atoms.

In an embodiment of the above-described polyclonal antibody which binds to a single-walled fullerene nanotube, wherein the fullerene is selected from the group consisting of a  
30 fullerene or derivative thereof comprising from 20 to 540 carbon atoms, the polyclonal antibody is a tip-specific antibody. In another embodiment of the above-described

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polyclonal antibody, the antibody is a side-wall specific antibody. In a further embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a C60 fullerene. In a still  
5 further embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a C70 fullerene. In yet another embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a C76  
10 fullerene. In another embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a C78 fullerene. In an embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a  
15 C82 fullerene. In yet another embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a C84 fullerene. In a further embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a C240 fullerene.  
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This invention provides a polyclonal antibody which binds to a multi-walled fullerene nanotubes, wherein the fullerene is selected from the group consisting of a fullerene or  
25 derivative thereof comprises from 20 to 540 carbon atoms.

In an embodiment of the above-described polyclonal antibody which binds to a multi-walled fullerene nanotubes, wherein the fullerene is selected from the group consisting of a  
30 fullerene or derivative thereof comprises from 20 to 540 carbon atoms, the fullerene carbon compound or derivative thereof comprises a C60 fullerene.

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In an embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a C70 fullerene. In another embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a C76 fullerene. In a further embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a C78 fullerene. In yet another embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a C82 fullerene. In an embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a C84 fullerene. In another embodiment of the above-described polyclonal antibody, the fullerene carbon compound or derivative thereof comprises a C240 fullerene.

All of the above described antibodies may be produced in a sheep, hog, goat, rabbit, guinea pig, mouse, rat and a human subject.

Polyclonal antibodies may be produced by injecting a host animal such as rabbit, rat, goat, mouse or other animal with the immunogen of this invention, e.g. a fullerene-protein conjugate, wherein the protein may be but is not limited to thyroglobulin, RSA, or BSA. The sera are extracted from the host animal and are screened to obtain polyclonal antibodies which are specific to the immunogen. Methods of screening for polyclonal antibodies are well known to those of ordinary skill in the art such as those disclosed in Harlow & Lane, Antibodies: a Laboratory Manual, (Cold Spring Harbor

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Laboratories, Cold Spring Harbor, NY: 1988) the contents of which are hereby incorporated by reference.

5 The monoclonal antibodies may be produced by immunizing for example, mice with an immunogen. The mice are inoculated intraperitoneally with an immunogenic amount of the above-described immunogen and then boosted with similar amounts of the immunogen. Spleens are collected from the immunized mice a few days after the final boost and a cell suspension is  
10 prepared from the spleens for use in the fusion.

Hybridomas may be prepared from the splenocytes and a murine tumor partner using the general somatic cell hybridization technique of Kohler, B. and Milstein, C., Nature (1975) 256:  
15 495-497. Available murine myeloma lines, such as those from the American Type Culture Collection (ATCC) 10801 University Blvd., Manassas, VA 20110-2209, USA, may be used in the hybridization. Basically, the technique involves fusing the tumor cells and splenocytes using a fusogen such as  
20 polyethylene glycol. After the fusion the cells are separated from the fusion medium and grown in a selective growth medium, such as HAT medium, to eliminate unhybridized parent cells. The hybridomas may be expanded, if desired, and supernatants may be assayed by conventional immunoassay  
25 procedures, for example radioimmunoassay, using the immunizing agent as antigen. Positive clones may be characterized further to determine whether they meet the criteria of the invention antibodies.

30 Hybridomas that produce such antibodies may be grown in vitro or in vivo using known procedures. The monoclonal antibodies may be isolated from the culture media or body

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fluids, as the case may be, by conventional immuno-globulin purification procedures such as ammonium sulfate precipitation, gel electrophoresis, dialysis, chromatography, and ultrafiltration, if desired.

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In the practice of the subject invention any of the above-described antibodies may be labeled with a detectable marker. In one embodiment, the labeled antibody is a purified labeled antibody. The term "antibody" includes, by way of example, both naturally occurring and non-naturally occurring antibodies. Specifically, the term "antibody" includes polyclonal and monoclonal antibodies, and fragments thereof. Furthermore, the term "antibody" includes chimeric antibodies and wholly synthetic antibodies, and fragments thereof. a "detectable moiety" which functions as detectable labels are well known to those of ordinary skill in the art and include, but are not limited to, a fluorescent label, a radioactive atom, a paramagnetic ion, biotin, a chemiluminescent label or a label which may be detected through a secondary enzymatic or binding step. The secondary enzymatic or binding step may comprise the use of digoxigenin, alkaline phosphatase, horseradish peroxidase,  $\beta$ -galactosidase, fluorescein or streptavidin/biotin. Methods of labeling antibodies are well known in the art.

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This invention provides an antibody specific for a fullerene, wherein the fullerene is selected from the group consisting of a fullerene carbon compound or derivative thereof comprising from 20 to 540 carbon atoms, wherein a radioactive material is encapsulated in the fullerene.

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Methods of encapsulating radioactive materials in fullerenes

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are known to one of skill in the art. For example Cagle, D.W. et al. (1999) PNAS (USA) 96:5182-5187 disclose the synthesis and use of radioactive metallofullerenes to monitor fullerene-based materials in vivo, wherein the radioactive material is holmium. One of skill in the art will recognize that radioactive materials other than holmium, e.g. gadolinium and other transition metals, may be encapsulated in fullerenes, including metallofullerenes.

This invention provides a method of determining a serum concentration of a fullerene in a subject which comprises:

- a) determining an amount of antibody which binds to the fullerene in the absence of serum;
- b) incubating a serum sample from a subject with an antibody which binds to the fullerene to form an antibody-fullerene complex;
- c) determining the amount of antibody which binds to the fullerene in the presence of serum by detecting the amount of fullerene complex;
- d) comparing the amount determined in step (c) with the amount determined in step (a), hereby determining the serum concentration of the fullerene in the subject.

In an embodiment of the above-described method of determining a serum concentration of a fullerene in a subject, the amount of antibody which binds to the fullerene in the absence of serum is determined for differing amounts of fullerene.

The determination of the amount of antibody which binds to the fullerene in the absence of serum fullerene allows one of skill in the art to prepare a standard curve for the

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amount of antibody which binds various known amounts of fullerene, so as to allow the comparison of the amount of antibody which binds to the fullerene in a serum sample. In another embodiment radioactive fullerene in differing known amounts may be used to determine the amount of antibody which bind thereto in the presence of "cold", i.e. nonradioactive fullerene, said amounts may be compared to the amount of antibody which binds to fullerene in a serum sample, thereby determining the amount of fullerene in the serum sample. For example the more nonradioactive fullerene (i.e. with larger amounts thereof) which binds to the antibody the lower the binding of the radioactive fullerene will be, allowing for the preparation of a standard curve with which to compare the presence of fullerene in a serum sample, which will bind in a manner similar to "cold" fullerene.

In an embodiment of the above-described method of determining a serum concentration of a fullerene in a subject, the detection of steps (a) and (c) is performed with a second antibody which binds to the antibody-fullerene complex, said second antibody being detectably labeled. In another embodiment of the above-described method of determining a serum concentration of a fullerene in a subject, the detectable label of the second antibody is selected from the group consisting of a radioactive isotope, enzyme, dye, biotin, a fluorescent label or a chemiluminescent label. In yet another embodiment of the above-described method of determining a serum concentration of a fullerene in a subject, the second antibody of step (c) is either a monoclonal antibody or a polyclonal antibody. In a further embodiment of the above-described method of



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determining a serum concentration of a fullerene in a subject, the second antibody is detectably labeled. In a still further embodiment of the above-described method of determining a serum concentration of a fullerene in a subject, the detectable label of the second antibody is selected from the group consisting of a radioactive isotope, enzyme, dye, biotin, a fluorescent label or a chemiluminescent label.

This invention provides a method of purifying a fullerene from a sample which comprises: a) preparing an affinity chromatography column to which are bound antibodies which bind to the fullerene; b) adding a sample to the affinity chromatography column so as to allow the sample to flow through the column, thereby permitting the fullerene to bind to the antibodies, thereby forming a fullerene-antibody complex on the column; and c) separating the fullerenes from the antibody-fullerene complex of step (b) by altering the pH, thereby purifying the fullerene from the sample.

In an embodiment of the above-described method of purifying a fullerene from a sample, the pH is lowered to approximately pH 3.0. In another embodiment of the above-described method of purifying a fullerene from a sample, the pH is raised to between approximately pH 9.0-10.0.

This invention provides a method of preparing a nanoscale device which comprises manipulating a single-walled fullerene nanotube or nanotubes with the above-described antibody which is specific for a single-walled fullerene nanotube, wherein the fullerene is selected from the group consisting of a fullerene or derivative thereof comprising

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from 20 to 540 carbon atoms, to assemble electronic or chemical components of the nanoscale device.

5 This invention provides a method of preparing a nanoscale device which comprises manipulating a multi-walled fullerene nanotube or nanotubes with the above-described antibody which is specific for a multi-walled fullerene nanotube, wherein the fullerene is selected from the group consisting of a fullerene or derivative thereof comprising from 20 to  
10 540 carbon atoms, to assemble electronic or chemical components of the nanoscale device.

In an embodiment of any of the above-described methods of preparing a nanoscale device which comprises manipulating a  
15 single-walled fullerene nanotube or nanotubes or of preparing a nanoscale device which comprises manipulating a multi-walled fullerene nanotube or nanotubes, the nanoscale device may be selected from the group consisting of a nanoscale optics device, a nanoscale electronic device, and  
20 a nanoscale biosensor device.

This invention will be better understood from the Experimental Details which follow. However, one skilled in the art will readily appreciate that the specific methods  
25 and results discussed are merely illustrative of the invention as described more fully in the claims which follow thereafter.

**EXPERIMENTAL DETAILS****First Series of Experiments**5       **MATERIALS AND METHODS**

The fullerene derivatives 1-4 relevant to this invention are shown in Fig. 1. Compounds 1 and 3 were prepared as described in ref. 16. For the synthesis of 2, see ref. 17.

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**Preparation of the Bovine Thyroglobulin (TG) Conjugate of**

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1. Compound 1 (1.5 mg, 1.6  $\mu$ mol) was dissolved in 0.25 ml of dry pyridine. *N*-Hydroxysuccinimide (Sigma) (8 mg, 70  $\mu$ mol) was added and brought into solution with the fullerene compound. Dicyclohexylcarbodiimide (Fluka) (6 mg, 43  $\mu$ mol) dissolved in 0.15 ml of dry pyridine was added, and the reaction was allowed to proceed at room temperature for 48 h. The reaction mixture then was added dropwise over a period of about 5 min to 10.4 mg (1.3  $\mu$ mol) of TG dissolved in 1 ml of water and adjusted to pH 9.5. The pH was kept at 8.5 throughout the reaction by the addition of 1 M NaHCO<sub>3</sub>. Some turbidity appeared during the reaction. The reaction was allowed to proceed for 4 h, and the reaction mixture then was dialyzed against PBS overnight at 4°C. The number of fullerene groups per molecule of TG was estimated, after clarification by centrifugation, to be ca. 20 by absorbance measurements at 320 nm (see below).

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**Bovine and Rabbit Serum Albumin (RSA) Conjugates.** Similar procedures were used for the BSA and RSA conjugates. The UV-Vis spectrum of the RSA conjugate is shown in Fig. 2. It has a peak at 254 nm and a shoulder at about 320 nm. Others

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have seen these fullerene characteristics, albeit with slight shifts in wavelength (11, 16-19). The rise after 254 nm is characteristic of polypeptides, as shown by the spectrum of an equal concentration of RSA in Fig. 2. In both cases the proteins were substituted with about 10 molecules of the fullerene derivatives per molecule of protein, as determined by UV-Vis spectral analysis at 320 nm and by titration of the unsubstituted amino groups by trinitrobenzenesulfonic acid (20).

Conjugation of 1 to Lys-Lys-Lys·3HCl (3L). *N*-Hydroxysuccinimide (0.5 mg, 4.3  $\mu$ mol) was dissolved in 0.125 ml of dry pyridine. The solution was added to 0.5 mg (0.54  $\mu$ mol) of 1, which then was allowed to dissolve. Dicyclohexylcarbodiimide (2.5 mg, 18  $\mu$ mol) was dissolved in 0.1 ml of dry pyridine, and the solution was transferred to the solution containing 1 and *N*-hydroxysuccinimide. The total reaction mixture was allowed to stand at room temperature for 48 h. It then was added dropwise to 0.1 mg (0.2  $\mu$ mol) of trilycine trihydrochloride (21) in 0.9 ml of 0.1 M NaHCO<sub>3</sub>, with stirring. The pH was kept at 8.5 by addition of the bicarbonate solution. The reaction was allowed to proceed for 4 h, and the resulting solution was taken to dryness over P<sub>2</sub>O<sub>5</sub> in vacuo. The resulting residue was taken up in 250  $\mu$ l of distilled water and clarified by centrifugation. Its UV-Vis spectrum is shown in Fig. 3. Like 1-RSA, it has a shoulder and a peak, albeit somewhat shifted. The shoulder is at 335 nm and the peak is at 260 nm. From both its spectrum and reaction of its free amino groups with trinitrobenzenesulfonic acid (20) it was found to have an average of 1.8 mol of 1 per trilycine molecule.

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Conjugation of I to Penta-L-Lysine (Sigma). This reaction was carried out in a similar fashion as the trilycine conjugation. The final product was substituted to the extent of 2.7 mol of 1 per pentalycine.

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**Immunization Procedure and Detection of Antibodies.** BALB/c mice were immunized i.p. with 1-TG in complete Freund's adjuvant for the primary immunization and incomplete adjuvant for subsequent immunizations.

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After a total of three immunizations at 3-week intervals, confirmation of an immune response was determined by direct ELISA in which polystyrene plates (Corning) were coated with the 1-RSA conjugate (0.5 mg/ml in 0.1 M NaHCO<sub>3</sub>, pH 9), and binding of preimmune and immune sera were determined by standard procedures. Development was with horseradish peroxidase-labeled goat anti-mouse IgG (Sigma), which tested negative for crossreaction with an IgM preparation. The substrate used was o-phenylenediamine.

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Specificity of the response was determined by two procedures: double diffusion in agar (22) and competitive inhibition, as determined by ELISA using RSA and BSA conjugates of the fullerenes, as well as the oligo lysine derivatives. The fullerenes themselves were not soluble enough in aqueous solutions.

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There were two controls for the ELISA experiments: (i) RSA, to show that the protein moiety did not participate in the inhibition, and (ii) adenosine-6-hexanoyl RSA (23), to show that the linkage group did not participate. The adenosine conjugate had been synthesized using the same strategy used

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for the fullerenes, i.e., linkage to the epsilon amino groups of the lysines via an *N*-hydroxysuccinimide ester derivative.

## 5 RESULTS

Immune Response to 1-TG. The immune response of mice immunized with 1-TG first was determined by ELISA. Because of the extreme hydrophobicity of fullerenes, it was important to show that nonspecific binding to serum components did not occur in the preimmune serum. The results are shown in Fig. 4 for sera taken from a BALB/c mouse immunized i.p. with one primary and two booster injections 3 weeks apart. The result was a high titer of specific antibody, as measured with 1-RSA. No antibody or nonspecific binding was seen with components of the preimmune serum. Development was with a peroxidase- labeled anti-mouse antibody specific for mouse IgG.

20 Specificity of the Immune Response. Specificity of the immune response first was determined by double diffusion in agar. The results are shown in Fig. 5.

Confluent lines of precipitation were seen associated with wells 1-5 with a spur between wells 2 and 3, pointing toward 3, i.e., toward 1-BSA. This finding is evidence of a population of antibodies reactive with both 1 and 2, with an additional population specific for the carrier protein of the immunogen, 1-TG. The identity of precipitation with 1 and 2 is evidence for the lack of participation of the linker group, which is missing from 2. a visible, albeit smaller, precipitate was seen with 3-RSA (well 5), the C<sub>70</sub>

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fullerene. Well 6, containing unsubstituted TG, showed no visible precipitate. However, when the TG solution was diluted 5-fold, a line of precipitation was seen (not shown), indicating a low titer of antibody specific for unsubstituted TG, i.e., in the original experiment (Fig. 5), i.e. TG was in antigen excess. Anti-TG also could be detected by ELISA (below).

Specificity also was determined by ELISA inhibition studies (Fig. 6). Binding to 1-RSA was inhibited by 1-RSA, 1-BSA, 1-TG, 3-pentalysine, 2-pentalysine, and 1-pentalysine. Inhibition by 2-pentalysine is additional evidence for nonparticipation of the linker group, i.e., specificity for the  $C_{60}$  moiety. Although not shown in Fig. 6 no inhibition was seen by TG, RSA. or adenosyl-6-hexanoyl-RSA, which has the same linker joining the hapten to the protein carrier (23).

In an additional control for specificity, the fullerene derivatives 1-pentalysine, 1-RSA, and 1-BSA were tested by ELISA for nonspecific inhibition of an antibody to a retinoic acid derivative (unpublished work) with its hapten-RSA conjugate. No inhibition by the fullerene derivatives was seen, in contrast to the inhibition seen with the retinoic acid derivative (data not shown).

Taken together, the results show that there was an IgG response directed at the fullerenes, and not at the functional groups linking the fullerenes to the carriers. Moreover, a subpopulation of the antibodies raised to a  $C_{60}$  fullerene crossreacted with the  $C_{70}$  fullerene.

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## DISCUSSION

Immunization of mice with a C<sub>60</sub> fullerene-TG conjugate produced a polyclonal response comprised of antibodies specific for C<sub>60</sub> fullerenes and a subpopulation that crossreacted with a C<sub>70</sub> fullerene derivative (Figs. 5 and 6). Detection was possible by ELISA using an IgG-specific second antibody showing that the antibodies raised were of the IgG isotype (Figs. 4 and 6). It follows from this that derivatization of TG by a fullerene molecule did not prevent intracellular processing and subsequent peptide display to T cells presumably by the process of linked recognition (24). Of interest is the manner of recognition of fullerenes by the immune system. Until we are in the position to examine the immune complex by direct means, e.g., x-ray crystallographic analysis, we can speculate based on characteristics of fullerenes that could provide potential for recognition.

*Hydrophobicity.* Fullerenes, being made up solely of carbon atoms, are very hydrophobic. It would be expected, therefore, that antibodies that recognize fullerenes will have hydrophobic amino acids in their binding sites. Such has been reported for the combining site of an Fab' fragment of a mAb specific for progesterone (25, 26), a molecule highly apolar in character (see below). Contact with amino acids in the combining site of the heavy chain included three tryptophans, one tyrosine, and a phenylalanine in a buried combining site of 254 Å<sup>2</sup> in surface area (26).

*Curvature.* Theoretical studies of various fullerenes show that curvature, expressed as the pyrimidalization angle  $P$ ,



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significantly influences fullerene properties and reactivity (27). Although the completely flat graphite molecule has a  $P$  angle of  $0^\circ$ , the most curved fullerene,  $C_{60}$  has angles uniformly bent at  $11.6^\circ$ . The angles of the  $C_{70}$  molecule vary from  $P = 8.8^\circ$  to almost  $12^\circ$  (see Fig. 1 for its shape). Curvature of a normally planar aromatic ring induces local charge differences.

*pi stacking.* The  $\pi$  system of fullerenes would be expected to interact with molecules in a combining site of an antibody via  $\pi$ -stacking interactions. Experimental data from the x-ray structure of a  $C_{60}$ /benzene solvate clearly show this kind of interaction (28). Three benzenes are associated with each  $C_{60}$  at distances of 3.27, 3.24, and 3.31 Å and are localized over the electron-rich interpentagon bonds. The  $C_{60}$  molecule is not rapidly "jumping" from one orientation to another as observed in the unsolvated  $C_{60}$  by neutron diffraction structure (29).

*Uneven charge distribution.* Although the charge distribution of  $C_{60}$  is necessarily uniform, the charge distribution of a mono-substituted  $C_{60}$  derivative such as 1 (Fig. 1) can show perturbations in its electron distribution (30). Moreover, it has been observed that  $C_{60}$  and other fullerenes interact with donor  $-NH_2$  and  $-SH$  groups (31, 32).

*Combining site fit.* We referred earlier to the interaction between progesterone and specific mAbs. The dimensions of  $C_{60}$  and progesterone are very similar. Progesterone is longer and somewhat narrower (5.8 Å by 13 Å) (26);  $C_{60}$  is a uniform sphere, 7.2 Å in diameter. The overall surface area, however, is very similar. There is no question about the

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"fit" of a fullerene in the combining site of an antibody.

Fig. 7 (Upper) shows the x-ray structure of an Fab' fragment of a monoclonal progesterone-specific antibody bound to 5 $\alpha$ -pregnane-20-one-3 $\beta$ -ol-hemisuccinate (26). The protein (Brookhaven PDB code 2DBL) is displayed as ribbons and the steroid as a space-filling model by using INSIGHT II (Molecular Simulations, San Diego, CA). The binding site is a large hydrophobic cavity lined with Trp, Phe, and Tyr groups. Using INSIGHT II, we replaced the steroid with C<sub>60</sub> to provide the model shown in Fig. 7 (Lower). As we did not relax the geometry using molecular dynamics, the fit is tight, but a slight side-chain adjustment would provide a very a good fit.

*Solvent displacement.* The free energy released on removing a hydrophobic surface from contact with water has been shown to correlate well with binding constants (33). Molecular modeling., studies of 4 (Fig. 1), a competitive inhibitor of an HIV protease, removed 298 Å<sup>2</sup> of solvent exposure (33). This stabilization reaction was mainly caused by carbon-to-carbon contacts with hydrophobic residues at the enzyme's active site: Leu, Ileu, Tyr, Trp, Pro, Gly, and Ala.

The question of the binding of C<sub>60</sub> and C<sub>70</sub> fullerenes to Fab' or Fv fragments of monoclonal antifullerene antibodies will be answered by x-ray crystallographic studies.

Finally, as part of this investigation three fullerene peptide derivatives have been prepared that are highly water soluble and have presented the UV-Vis spectra of two of

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them.

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**Second Series of Experiments**

The conjugate, C<sub>60</sub>-thyroglobulin, is prepared as described below in "Preparation of Polyclonal Antibodies Specific for Fullerenes". In those studies, polyclonal IgG antibodies were elicited in mice. a major population showed specificity for the C<sub>60</sub> hapten; a subpopulation reacted with C<sub>70</sub>. Therefore, hybridomas that produce monoclonal antibodies specific for C<sub>60</sub> fullerenes and others specific for C<sub>70</sub> fullerenes may be isolate. On the other hand, it is not clear that the reaction with C<sub>70</sub> was not just a cross-reaction, i.e. a population of anti-C<sub>60</sub> antibodies that cross-reacted with C<sub>70</sub>. This possibility is taken into account during the screening process.

Alternatively, antibodies specific for C<sub>70</sub> fullerenes may be obtained by immunizing with a C<sub>70</sub>-thyroglobulin conjugate. Here, too, however, the possibility of C<sub>60</sub> and C<sub>70</sub> cross-specificity exists. One interest, in this case, is to obtain C<sub>70</sub> specificity. Screening for specificity is by ELISA using RSA conjugates of the C<sub>60</sub> and C<sub>70</sub> fuller-ene derivatives shown in Fig. 1 of the first series of experiments.

Immunization of BALB/c mice is according to a protocol used to obtain the polyclonal anti-fullerene antibodies (see above), with thyroglobulin as the carrier protein, i.e. 1-TG (see Fig. 1, first series of experiments, for structure of 1). Primary immunization is by subcutaneous injection in Freund's complete adjuvant, followed three weeks later by a booster injection in incomplete Freund's adjuvant. Usually two additional booster injections, two weeks apart are

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sufficient to raise a sufficiently high titer of specific antibody (assayed against the 1-RSA by ELISA) to start the hybridoma protocol.

5 The mouse is sacrificed, its spleen removed and spleen cells fused with a non-producer mouse myeloma, P3x63-Ag8.613, using PEG 1000 according to the procedure of Sharon et al (1). The cells are placed in 96 well plates and, after two weeks incubation at 37 °C, the supernatants are assayed by  
10 ELISA for binding to 1-RSA. Cells in positive wells are subcloned twice by limiting dilution and positive clones are isolated and grown in 96 well plates, then 24 well and finally in flasks, being assayed along the way.

15 Specificities for C<sub>60</sub> fullerenes and cross reactions with C<sub>70</sub> fullerenes are determined by ELISA. The specific aim is to isolate antibodies to C<sub>60</sub> that do not cross react with C<sub>70</sub> compounds. Immunization may also be performed with C<sub>70</sub>-TG and selection for monoclonal antibodies with C<sub>70</sub> specificity may  
20 be accomplished.

The possibility of covalent linkage between fullerenes and a specific monoclonal antibody (above) is raised and can be tested for that in a preliminary way as follows:

25 Incubate aliquots of monoclonal antibody with fullerene-trilysine for periods of 2h-24h. After dialysis against PBS for 24 h to remove unbound fullerene, the aliquots are assayed for binding to fullerene-RSA by ELISA. Covalent  
30 linkage would be indicated by a decrease in binding with time of incubation with fullerene-trilysine. The control will be antibody incubated for the same periods of time, but



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in the absence of fullerene-trilysine. Of course, unambiguous evidence of covalent linkage will be provided by the proposed x-ray crystallographic studies.

5      **Preparation of Fab' and Fv fragments of monoclonal antibodies**

10      a) Fab' fragments - The specific monoclonal antibody are converted into an Fab' fragment after purification on a DEAE-cellulose column in phosphate buffer, pH 8.0. The IgG antibody leaves the column at the void volume. This is followed by digestion with papain in the presence of mercaptoethanol at 37 °C (enzyme: substrate =1:100). The course of digestion is followed by SDS-gel electro-phoresis.

15      The Fab fraction is then purified on a DEAE-cellulose column, precipitated with  $(\text{NH}_4)_2\text{SO}_4$  and dialyzed against 0.01M potassium phosphate, pH 7.0. This is essentially the procedure used by Mariuzza et al. (2) for the preparation of Fab from a monoclonal anti-lysozyme antibody. The Fab was

20      used in X-ray crystallographic studies. The Fab purification may also be done by carboxymethyl cellulose column (Porter, 1951, Biochem. J.)

25      b) Fv fragments are most suitably produced by molecular biological procedures as a recombinant protein. The variable chains that make up the Fv fragment can best be prepared by PCR cloning with the appropriate primers and expression either in bacteria (E. coli) or in eukaryotic cells. Enzyme digestion (e.g. pepsin) has been found to be

30      less reliable.

With respect to expression in E. coli, one of skill may use

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the procedure of Orlandie et al. (3). In this procedure, RNA is isolated from about  $10^6$  hybridomas cells using guanidinium isothiocyanate. This is followed by reverse transcription of total mRNA using an oligo(dT) primer and then amplification of the resulting cDNA by PCR, using degenerate oligonucleotides based on conserved regions at the 5' end of V gene segments and the 3' side of the J segments. This is then followed by cloning of the amplified  $V_H$  and  $V_L$  genes in the pUC19-based dicistronic vector pSW1. It is in frame with the signal sequence of pectate lyase to allow secretion into the endoplasmic space of *E. coli*. Sequencing of several clones is necessary to ensure that random mutations have not occurred. This procedure was used by Goldbaum et al. to prepare Fv fragments for preliminary x-ray analysis of Fv-Fv complex (4, and see below).

One of skill may also use the cloning procedure developed by Coloma et al. (5, 6). This procedure allows for expression in non-producer myeloma cell lines such as NS2 or P3X63-Ag8.653. Most of applicants' hybridoma experience is with the latter line and therefore, this procedure is preferred for expression of the Fv fragments.

The fullerene derivative co-crystallized with the Fab and Fv fragments of the antibody.

The synthesis of a trilylsine derivative of the  $C_{60}$  fullerene compound 1 has already been described (see below). This derivative is, however, a mixture with an average substitute of 1.8 fullerenes per trilylsine. For the co-crystallization experiments, to work with the monosubstituted derivative is preferred. The separation of the pure monosubstituted

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compound from the mixture can be accomplished by reverse phase or ion exchange chromatography because the various components of the mixture differ in hydrophobicity and charge.

5

#### **Preparation of Polyclonal Antibodies Specific for Fullerenes.**

10 The fullerene derivatives 1-4 used in the studies relevant to this invention are shown in Fig. 1. Compounds 1-3 were prepared as described in ref. 16, first series of experiments. For the synthesis of 2, see ref. 17, first series of experiments.

#### **15 Preparation of the bovine the thyroglobulin (TG) conjugate of 1.**

Compound 1 (1.5 milligrams, 1.6 u moles) was dissolved in 0.25 ml of pyridine. N-Hydroxysuccinimide (Sigma Chemicals  
20 St. Louis, MO) (8 mg, 70 u moles) was added and brought into solution with the fullerene compound. Dicyclohexylcarbodiimide (Fluka Chemicals, Buchs, Switzerland) 6 mg, 43 u moles) dissolved in 0.15 ml of dry pyridine was added and the reaction allowed to proceed at  
25 room temperature for 48 h. The reaction mixture was then added dropwise over a period of about 5 min to 10.4 mg (1.3 u moles) of TG dissolved in 1 ml of water and adjusted to pH 9.5. The pH was kept at 8.5 throughout the reaction by the addition of 1M NaHCO<sub>3</sub>. Some turbidity appeared during the  
30 reaction. The reaction was allowed to proceed for 4h and the reaction mixture was then dialyzed against PBS overnight at 4°C. The number of fullerene groups per molecule of TG was estimated after clarification by centrifugation to be

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ca. 20 by absorbance measurements at 320 nm (see below).

**Bovine and rabbit serum albumin conjugates.** Similar procedures were used for the bovine serum albumin (BSA) and rabbit serum albumin (RSA) conjugates. The uv-vis spectrum of the RSA conjugate is shown in Fig. 2, first series of experiments. It has a peak at 254 nm and a shoulder at about 320 nm. Others have seen these fullerene characteristics, albeit with slight shifts in wavelength (11, 16-19, first series of experiments). The rise after 254 nm is characteristic of polypeptides, as shown by the spectrum of an equal concentration of RSA is Fig.2. In both conjugates the proteins were substituted with about 10 molecules of fullerene derivatives per molecule of protein, as determined by uv-vis spectral analysis at 320 nm and by titration of the unsubstituted amino groups by trinitrobenzenesulfonic acid (20, first series of experiments).

**Conjugation of 1 to Lys-Lys-Lys·3HCl (3L).** N-Hydroxysuccinimide (0.5 mg; 4.3  $\mu$  moles) was dissolved in 0.125 ml of dry pyridine. The solution was added to 0.5 mg (0.54  $\mu$  moles) of 1, which was then allowed to dissolve. Dicyclohexylcarbodiimide (2.5 mg; 18  $\mu$  moles) was dissolved in 0.1 ml of dry pyridine and the solution transferred to the solution containing 1 and N-hydroxysuccinimide. The total reaction mixture was allowed to stand at room temperature for 48 h. It was then added dropwise to 0.1 mg (0.2  $\mu$  moles) of tryllysine trihydrochloride (21, first series of experiments) in 0.9 ml of 0.1 N NaHCO<sub>3</sub>, with stirring. The pH was kept at 8.5 by addition of the bicarbonate solution. The reaction was allowed to proceed

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for 4 h, and the resulting solution taken to dryness over  $P_2O_5$  in vacuo. The resulting residue was taken up in 250 ul distilled water and clarified by centrifugation. Its uv-vis spectrum is shown in Fig. 3, first series of experiments. Like 1-RSA, it has a shoulder and a peak, albeit somewhat shifted: The shoulder is at 335 nm and the peak is at 260 nm. From both its spectrum and reaction of its free amino groups with trinitrobenzenesulfonic acid (20, first series of experiments) it was found to have an average of 1.8 molecules of 1 per trilysine molecule.

**Conjugation of 1 to penta-L-lysine (Sigma, St. Louis, MO).** This reaction was carried out in a similar fashion as the trilysine conjugation. The final product was substituted to the extent of 2.7 molecules of 1 per pentalysine.

**Immunization procedure and detection of antibodies.** Balb/C mice were immunized i.p. with 1-TG in complete Freund's adjuvant for the primary immunization and incomplete adjuvant for subsequent immunizations.

After a total of 3 immunizations at 3 week intervals, confirmation of an immune response was determined by direct ELISA in which polystyrene plates (Corning) were coated with 1-RSA conjugate (0.5 mg/ml in 0.1 N  $NaHCO_3$ , pH 9) and binding of preimmune and immune sera determined by standard procedures. Development was with horseradish peroxidase-labeled goat anti-mouse IgG (Sigma, St. Louis, MO). which tested negative for cross reaction with an IgM preparation. The substrate used was o-phenylenediamine.

Specificity of the response was determined by two

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procedures: Double diffusion in agar and competitive inhibition, as determined by ELISA using RSA and BSA conjugates of the fullerenes, as well as the oligo lysine derivatives. The fullerenes themselves were not soluble enough in aqueous solutions.

There were two controls for the ELISA experiments: 1) RSA, to show that the protein moiety did not participate in the inhibition; 2) adenosine-6-hexanoyl RSA (23, first series of experiments), to show that the linkage group did not participate. The adenosine conjugate had been synthesized using the same strategy used for the fullerenes, i.e. linkage to the epsilon amino groups of the lysines via an N-hydroxysuccinimide ester derivative.

**The Immune response to 1-TG.** The immune response of mice immunized with 1-TG was first determined by ELISA. Because of the extreme hydrophobicity of fullerenes, it was important to show that non-specific binding to serum components did not occur in the pre-immune serum. The results are shown in Fig. 4 (first series of experiments) for sera taken from a Balb/C mouse immunized i.p. with one primary and two booster injections three weeks apart. The result was a high titer of specific antibody, as measured with 1-RSA. No antibody or non-specific binding was seen with components of the pre-immune serum. Development was with a peroxidase-labeled anti-mouse antibody specific for mouse IgG.

**Specificity of the immune response.** Specificity of the immune response was first determined by double diffusion in agar. The results are shown in Fig. 5 (first series of

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experiments). Lines of precipitation were seen associated with wells 1-5 with a spur between wells 2 and 3, pointing toward 3, i.e. toward 1-BSA. This implies an additional reactive epitope in 1-TG, not present in the BSA conjugate.

5 A visible, albeit small precipitate was seen with 3-RSA (well 5). Well 6, containing unsubstituted TG showed no visible precipitate. However, when the TG solution was diluted five-fold, a line of precipitation was seen (not shown), indicating a low titer of antibody specific for

10 unsubstituted TG, i.e. in the original experiment (Fig. 5, first series of experiments) TG was in antigen excess. Moreover, anti-TG could be detected by ELISA (below).

Specificity was also determined by ELISA inhibition studies

15 (Fig. 6, first series of experiments). Binding to 1-RSA was inhibited by 1-RSA, 1-BSA, 1-TG, 3-pentalysine and 1-pentalysine. No inhibition was seen by TG, RSA, or adenosyl-6-hexanoyl-RSA, which has the same linker joining the hapten to the protein carrier (23, first series of

20 experiments). As an additional control for specificity, 1-RSA, 1-pentalysine and 1-BSA were tested by ELISA as non-specific inhibitors of an antibody to retinoic acid (unpublished). No inhibition was seen, in contrast to inhibition by retinoic acid.

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### Third Series of Experiments

The objective of these studies is to prepare and screen antibodies to carbon clusters and nanotubes: fullerene compounds C60, C 70, C240 and [10, 10]-nanotubes. It is expected that C240-specific monoclonal antibodies (MAB's) can be used to recognize the tips and/or side walls of single wall nanotubes (SWNT's). The interactions of carbon clusters and nanotubes with these biomolecules by a variety of means, including protein X-ray crystallography are to be characterized. MAB's to single-wall nanotubes (SWNT's) may be used to develop assays that will accelerate SWNT processing, applications, and commercialization. Finally, basic science issues involving the future use of antibodies as assemblers are explored that will allow programmed assembly of nanotubes at the nanometer and mesoscopic scale.

Carbon clusters and nanotubes: The discovery of a new form of carbon fullerene-C60 in 1985 by Smalley and coworkers at Rice University stimulated tremendous world-wide research interest.[1] When the Huffman-Kratschner (HK) arc process for production of fullerene-C60 in quantity made samples of C60 available in 1991, scientists throughout the world began to explore C60 chemistry. Close relatives of C60, fullerene nanotubes (very long graphitic molecular fibers), were first observed in the HK arc process by lijima [2]. Numerous theoretical and microscopic studies of nanotubes followed this exciting discovery [3]. However, it was the recent breakthrough by Smalley --preparation of gram quantities of fullerene single wall nanotubes (SWNT) --that promises to propel SWNT research to commercial application. SWNT's are called "the perfect carbon fibers." They conduct electricity

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as well as gold, and are 100X stronger than steel at 1/6 the density. Important DoD-related applications include mechanical/chemical applications as well as optical/electronic. Possible uses are light weight, high strength composites for vehicle body panels, ship hulls and airframes, ship and helicopter propellers, rocket nozzles, helmets and body armor. Electronic/optical applications could include tactical displays, laser eye protection, vacuum electronics, capacitors, batteries and fuel cells. Other uses may be chemical filters, catalyst supports, hydrogen storage and nanoscale devices for computation. [4]

The enormous promise of SWNT's requires the development of many supporting basic science areas to assist in characterization and to begin evaluation of potential biological applications and potential health risks. Considerable work is known about C60 chemistry and much work has been done on toxicology and even drug development with fullerenes. [5] The toxicology of large carbon fibers has been extensively studied and a review is available. [6] Nothing at all is known about toxicology of SWNT's or their interactions with biological systems. While no general toxic effects of fullerenes are known, the small diameter and very large aspect ratio (ratio of length to diameter) somewhat reminiscent of asbestos fiber, make an important side-benefit of this research the beginning first steps to the understanding of the relationship of SWNT's to human health.

Antibodies: while there is not enough space here to even begin to review the field of immunology, it can be simply pointed out that cells of the immune system can produce such

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antibodies in response to foreign molecules called antigens. Antibodies are protein molecules of molecular weight~150,000 and are created by antibody-producing cells to bind strongly to an antigenic foreign molecule. Antibodies produced directly by animal immunization are polyclonal since they are produced by a multiplicity of cells that respond to the presence of the antigen. Techniques are also available for the preparation of monoclonal antibodies (MAB). MAB's are prepared from a single cloned cell line and thus only one pure molecular form of the antibody is obtained. MAB's are desirable since they are pure molecules, can be crystallized, and molecular biological techniques be used to sequence their gene of the MAB, study, characterize, model, and modify the structure, and prepare crystals for X-ray crystallography.

The development of methods for the preparation of antibodies to hydrophobic small molecules is well known to one of skill in the art. [7] During the 1950's and 60's Erlanger developed the approach of linking steroid molecules to serum albumins, to immunize rabbits with the steroid-serum albumin conjugate, and to thereby obtain specific anti-steroid antibodies. This method has revolutionized detection of hydrophobic compounds in biological systems. In his latest work, Erlanger has prepared monoclonal antibodies to the hydrophobic molecule taxol was well a MAB that mimics taxol. [8]

Approach and Preliminary studies: Carbon cluster and nanotube antibodies are to be prepared and MAB to selected fullerenes have been crystallized. It is possible to produce X-ray quality crystals and to determine the complete 3D

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structure of these antibodies (see for example Fig. 23 which shows the 3D structure of the active site of an anti-fullerene monoclonal antibody). Antibodies to SWNT's can be imagined to consist of two classes: tip-specific antibodies and side-wall specific antibodies. Tip-specific antibodies are prepared using antibodies produced using a related fullerene hapten. The tips of [10,10]-SWNT's are predicted to be hemi-fullerenes, specifically one half of a C240 molecule. Although C240 has been detected by mass spectrometry and STM, it has not yet been isolated. [8,9] Vigorous work in that area is continuing. Currently only C60, C70, C76, C78, and C84 are available in commercial quantities.

While C240 is much larger than C60 (see Figure 8) it is well within the molecular scale of known antibody combining sites. An antibody to dextran binds 5 glucose residues which corresponds to a combining site 2.5 nm long. (The taxol anti-idiotypic antibody shown in figure 2 and discussed later binds to tubes 25 nm in diameter.) [8]

Considerable chemistry is now known about C60, and so the first experiments used this simplest fullerene. Preliminary studies are very encouraging and indicate that excellent polyclonal antibodies can be prepared by essentially conventional methods. Fullerene C60 was treated as a hapten and covalently linked to bovine serum albumin (BSA) and rabbit serum albumin (RSA) in order to induce a T-dependent immune response which can lead to high affinity antibodies. Linkage to BSA and RSA was performed via an N-hydroxy succinimide ester derivative of C60. A rabbit was immunized with BSA-fullerene conjugate dissolved in aqueous solution and emulsified with Freund's adjuvant. This mixture was

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injected intradermal in multiple regions of the back of a rabbit. This initial immunization was followed by three booster immunizations. Serum drawn from the rabbit was tested for fullerene-specific antibodies using the RSA conjugate of fullerene-C60. This was done because the rabbit does not make antibodies to its own protein, RSA. Hence any reaction will be directed at the fullerene-C60 moiety. The antibodies were detected using an ELISA techniques. Recognition of the water soluble anti-viral fullerene derivative, originally synthesised by Wudl, by the C60 specific antibodies has been demonstrated.

The goal of these studies is to develop methods to prepare high-affinity monoclonal antibodies to fullerene clusters and carbon nanotubes and to characterize their interactions by a variety of means including X-ray crystallography. This work explores the application of antibodies to manipulation of nanotubes.

The long range goal of this program is to design an antibody-based nanotube analysis system and create a nanoassembler system that could assist in the organization of SWNT's into useful nanoscale devices. Fullerene antibodies serve as the basis for an important enabling science--connecting the "dry-side" of nanotechnology with the "wet-side" i.e. biology. Initially prepared and characterized are the antibodies to the simplest fullerene-C60 and to SWNT's. This enables learning more about how best to link, solubilize, and characterize antibodies to carbon clusters and SWNT's develop new methods for fundamental problems in analysis of SWNT structures-for example to allow the distinction, with specific antibodies, between [10,10]

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tubes and [n,m] tubes.

Technology to use monoclonal antibodies (MAB) to allow assembly and organization of carbon clusters and SWNT's into large mesoscopic arrays producing useful devices are also encompassed within the scope of the present invention. This use is widely promoted in nanotechnology, and may possible by harnessing monoclonal antibody technology to do it. A good demonstration has already ben accomplished. Cell division (mitosis) is mediated by a complex tubulin by the mediation of a small hydrophobic molecule called Taxol. Erlanger has shown this process can also be carried out by an anti-idiotypic antibody which mimics the action of taxol and stimulates the process of micro-tubule organization as shown in Figure 2. It is suggested that tip-specific and side-wall specific SWNT MAB's of various sorts may be developed as "nano-assemblers" for the arrangement of SWNT-based devices. It may be possible to reconstitute catalytic MAB's antibodies that operate in organic media to promote the assembly and orientation of SENT's into useful nanoscale devices on the surface of silicon chips.[11]

Figure 9 shows an electro-microgram of micro-tubules with y-shaped MAB's bound to them along the side-walls. Theses fibers are grown in-situ in response to the taxol-like MAB factors. The dimensions of micro-tubules are on the order of 25nm, similar to multiwall carbon nanotubes, although larger that SWNT.

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**Fourth Series of Experiments**

Radioimmunotherapy (RIT) has the potential to deliver doses of highly energetic radiation specifically to cancerous growths, thereby eliminating the radiative damage to healthy tissue common during externally delivered radiation therapy. The traditional method for RIT is to link a radioactive atom to a monoclonal antibody (mAb) specific for the tumor, and inject it into the patient. The mAb then circulates until it binds to the tumor, where the radionuclide decays, emitting radiation to destroy the cancer cells. To date, the radioactive metal atoms have been bound to a chelating molecule, which is in turn linked to the mAb specific to the epitope on the tumor. Similar methods have been developed for radioimmunoimaging (RII), where a gamma ray emitter is bound to the chelating compound, and scintigraphy is used to detect the concentrated areas of gamma rays which mark the tumor.

Unfortunately, in the methods developed to date, almost none of the administered radioactive dose reaches the cancer. As a result, clinical trials have shown poor response rates to RIT against solid malignancies (Wilder et. al., 1996). In conventional methods, the primary problem is the long time required for the mAb to find the cancer cells. While the mAbs circulate, a significant fraction of the radionuclides decay, damaging healthy tissue and resulting in low tumornontumor (T:NT) ratios of radioactivity. Further, the linker can be metabolized, separating it from the mAb, and/or the metal can become unchelated, both of which release radionuclides that will never reach the tumor.

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Complete containment of the radionuclide can be achieved by using endohedral metallofullerenes (Figure 10) Fullerenes are the third allotrope of carbon, a class of nearly spherical cages roughly one nanometer in diameter. The high strength of the carbon  $sp^2$  bonds and durability of the fullerenes ensure that the encapsulated metal atom remains in the cage, even under beta recoil energies in excess of 10 eV (Kikuchi et. al., 1994). The cage can be functionalized to become water-soluble without loss of integrity. Since the metal cannot escape a fullerene cage, isotopes with longer half-lives can reduce background radiation doses by allowing the mAb more time to find the cancer before decay occurs. These properties make fullerenes an attractive option to replace chelators for the delivery of radionuclides.

Multi-step targeting has shown promise as a means of increasing the T:NT ratio. The first injection in these methods is a bispecific antibody, where one end binds to the tumor and the other is specific for the chelating agent. The chelated radionuclide is injected later, after the bispecific antibody has achieved its maximum localization on the tumor. These methods suffer from the same problems that release radionuclides, but for a shorter time. Since the advantage is gained by using more rapidly circulating (and clearing) radiolabeled molecules, the smallest molecule that can firmly chelate the radionuclide and be specific for its receptor is desirable. In these respects, metallofullerenes are also ideal for radionuclide delivery in multi-step targeting.

Very recently, antibodies to empty fullerenes were developed by molecular bioengineering, providing a receptor for the

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metallofullerene. These new molecular tools prompted us to design an improved method for administering RIT: the radioisotope-containing water-soluble fullerene is administered after a bispecific antibody, where one end is the fullerene antibody (Abf), and the other is the tumor-specific mAb, has achieved its maximum localization on the tumor. Since the binding strength of the essentially hydrophobic fullerene to its own antibody can be very high, and water-soluble fullerenes will circulate rapidly without strong retention in any particular organ, this is a promising way to improve the T:IT ratio.

The specific aim of this research is to show that the metallofullerene  $\text{Ho@C}_{82}$  (one holmium atom inside of a carbon cage containing 82 carbon atoms) can be derivitized to become water-soluble, and then bound to the bioengineered Abfs.  $\text{Ho@C}_{82}$  will be bound to a monoclonal antibody bioengineered specifically for  $\text{C}_{82}$  containing a metal atom. The available Abf at present is polyclonal produced in response to  $\text{C}_{60}$ , the most abundant fullerene. It is non-reactive with  $\text{C}_{70}$ , but not as yet been tested with  $\text{C}_{82}$ . The  $\text{C}_{82}$  fullerene has been chosen as a host for the lanthanide because methods for its purification are much better developed than for other endohedral metallofullerenes. Virtually all lanthanides can be encapsulated with equal ease: holmium was selected because therapeutic applications of the  $^{166}\text{Ho}$  isotope have already been proposed. The process of neutron activating  $(\text{Ho@C}_{82})\text{R}$  (where R is a group inducing water solubility) to become  $(^{166}\text{Ho@C}_{82})\text{R}$  is currently being studied. The attachment of metallofullerenes to antibodies is also to be studied.

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Metallofullerene-based RIT treatments is one long term goal of these studies and precedents for mAb-based cancer therapies have already been established. For example, the mAb B72.3, developed at the National Cancer Institute, has been approved by the FDA and licensed by the NIH to pharmaceutical companies. Cytogen Corp. employs it as a basis for diagnostic agents for the detection and imaging of colo-rectal and ovarian cancers. More advanced, second generation antibody technology (CC49, e.g.) is also becoming available and is currently licensed for RII and RIT applications. Bispecific antibodies, such as MDX-210 (Medarex, Inc.) and 2B1 (Chiron Corp.), are also receiving approval for cancer therapies involving a triggering of the patient's own immune system.

Endohedral fullerenes and their produced derivatives may be purified and used in the methods developed in this study. Endohedral fullerenes are predicted to exhibit many unique properties that make them potentially valuable commodities.

As an example, calculations predict that  $C_{80}$  containing trapped lanthanide ions will be a high temperature superconductor.

With respect to medical markets, all applications involving the transport of metals in vivo can benefit from metallofullerenes. Ho@fullerene based materials may be used as radionuclide carriers and a specific use may be as labeling agents. Lanthanide-encapsulated fullerenes may also have potential use as labels that are detected by lanthanide fluorescence. Potential uses include fluorescent labels for tagging of amino acids, antibodies, nucleic acids, and other molecules used in enzymatic analysis,

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immunoassays, or DNA and protein sequencing applications. The fullerene label would also be useful in industrial applications requiring lanthanide labels that can survive extreme chemical environments.

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Of all applications proposed for endohedral metallofullerenes, their use as radionuclide labels appears to be the most promising. Metallofullerenes are currently quite expensive to produce and purify. Therefore, potential near term applications need to be high value and require only small amounts of material. Radionuclide labels for immunoguided applications fit this requirement exactly. Medical applications are intrinsically high valued, and the amount of material required is extremely small ( $\mu\text{g}$ 's or less). With future improvements in the areas of metallofullerene production and purification, the cost should be lowered within the next few years. Then the use of a metallofullerene label with a monoclonal antibody would contribute only a small fraction to the total cost of the treatment.

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The present studies are made to demonstrate that endohedral metallofullerenes can be linked to antibodies. The results of this study have significant implications for all applications involving transport of toxic metals in vivo. This research will lead to the development of a new method of transport of toxic metal atoms in vivo, possibly providing an improved method of guiding the radionuclide to the tumor in RIT and RII.

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## B. Significance

This section begins with a review of metallofullerenes, highlighting their potential and limitations for RIT. Replacing chelates with metallofullerenes requires a significantly different, but probably advantageous, procedure for the attachment of the radionuclide to the mAb. Many targeting strategies for RIT have been developed; to focus on the correct one requires significant knowledge of the binding strengths, specificity, and pharmacokinetics of the different pieces of the metallofullerene - bispecific antibody being assembled. The available fullerene biodistribution studies, important if multistep targeting approaches are considered, all conclude that fullerenes are nontoxic. The distributions are dependent on the functionality used to induce water solubility in the fullerene. The process used to create antibodies to fullerenes is then summarized, including studies demonstrating the high specificity of the antibodies. This series of experiments concludes with an outline of potential strategies for RIT based on a fullerene carrying the radionuclide.

**B.1 Metallofullerene Background** Fullerenes are a new class of hollow, closed shell, all carbon molecules discovered by R.E. Smalley and co-workers in 1985 (Kroto et al. 1985). The feasibility of encapsulating metal atoms inside the fullerenes was proven by Smalley's group (Heath et al. 1985) shortly after their initial discovery. Subsequent gas phase photofragmentation experiments showed that fullerenes are among the most stable molecules known to exist, able to store up to 50 eV (delivered by photon

-70-

bombardment) in internal energy (Wurz and Lykke, 1992). The first bulk amounts of fullerenes were synthesized by resistive heating of graphite in an inert He atmosphere in 1990 by Huffman and Kratschmer (Kratschmer et al. 1990).

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Bulk quantities of fullerenes containing La atoms were first synthesized by R. E. Smalley's group in 1991 (Chai et al. 1991). The first metallofullerene samples were produced by laser vaporization of  $\text{La}_2\text{O}_3$  impregnated graphite rods in a tube furnace at  $1200^\circ\text{C}$ . Later experiments demonstrated that endohedral fullerenes could also be produced in usable amounts by the conventional arc evaporation of metal oxide or metal carbide impregnated graphite rods (Johnson et al. 1992). Electron paramagnetic resonance (EPR) studies of toluene soluble  $\text{La@C}_{82}$  later proved that the La atom was in the +3 valence state with the fullerene functioning as a compensating anion (Johnson et al. 1992). Recent x-ray diffraction studies on  $\text{Y@C}_{82}$  prove conclusively that the metal atoms are encapsulated inside the fullerene (Takata et al. 1995).

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It has since been shown that it is possible to produce bulk amounts fullerenes containing Ca, Sr, Ba, Sc, Y La=lanthanides, and U as well as fullerenes containing multiple metal atoms such as Y dimer and Sc trimer (Bethune, 1993). In general, the production of metallofullerenes creates a broad range of endohedral species containing from 60 to 200 carbon atoms and one or more metal atoms. However, attempts at large-scale encapsulation of metals outside of Group II and Group III have met with little success. High pressures can induce noble gas atoms to enter the cage in very small quantities (Saunders et al. 1996). A

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recent report of  $^{99m}\text{Tc}$  encapsulation (Karem et al., 1997) lacks the definite photofragmentation test (Heath et al., 1986) to prove encapsulation rather than external complexation.

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Metallofullerenes are made using stable isotopes of the Lanthanides (Section D.1 infra), and later activated under a slow neutron flux to form radionuclides. By first producing, purifying, and derivitizing the non-radioactive metallofullerene, the time from acquisition of the radionuclide to its administration for RIT is greatly reduced. Thermal neutron activation of  $^{165}\text{Ho}@C_{82}$  fullerenes has been used to create  $^{166}\text{Ho}@C_{82}$  fullerenes with up to 8% survivability after 5 hours of irradiation under a flux of  $4 \times 10^{13}$  neutrons/cm<sup>2</sup>/s (Cagle et al., 1996). The low yield appears to be due to the fast neutron component, perhaps 25% of the neutrons, although recoil from prompt gamma emission may also play a role in degradation of the fullerene cage. The present studies are extended to include  $\text{Ho}@C_{82}$  fullerenes derivitized to be water soluble. Neutron activation of endohedral metallofullerenes offers a viable path for encapsulation of radionuclides, but further restricts the choice of radionuclide to one that can be readily produced by neutron activation. However, the surviving metallofullerenes are ready for immediate use, whereas the slow uptake of short-lived isotopes into chelates reduces their effectiveness.

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Despite the limitations imposed by the elements which can be encapsulated and then neutron activated, a wealth of potential radionuclides remain. Table 1 depicts the potential lanthanide beta-emitters with a thermal neutron



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capture cross sections of about 10 barns. The  $^{166}\text{Dy}/^{166}\text{Ho}$  pair is particularly intriguing, as it offers the chance to deliver two  $\beta^-$  particles per radionuclide.

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Table 1

5	Isotope	Production Cross Section (barns)	half life	$\beta$ -energy (MeV)
10	$^{140}\text{La}$	9	40 h	various; to 2.2
	$^{142}\text{Pr}$	12	19 h	2.2
	$^{166}\text{Dy}$	1000*	82 h	0.5
	$^{166}\text{Ho}$	65#	27 h	1.8
	$^{170}\text{Tm}$	105	129 d	1
	$^{175}\text{Yb}$	65	4.2 d	0.5
15	$^{177}\text{Lu}$	25*	7d	0.5

Table 1: Potential lanthanide radioisotopes. \* indicates that two steps are required, but the second step has a cross section of at least 1000b. # indicates that it is also produced as the daughter of the  $^{166}\text{Dy}$  decay. All production cross sections are based on neutron capture by the A-1 isotopes.

Unlike chelates, fullerene cages withstand recoil energies between 10 and 100 eV (Kikuchi et al., 1994). Early studies suggested that a recoil energies less than an electron volt are likely to rupture chelating bonds (Asano et al., 1974; Glenworth and Betts, 1969; Glenworth and 1961), although more recent work asserts that all of the  $^{166}\text{Ho}$  formed from  $^{166}\text{Dy}$  decay (recoil energy of 1.85 eV) is retained in the DPTA chelate (Smith et al., 1995). Highly energetic decays with larger recoil energies are desirable because they improve the dose per radioisotope, as long as the radiated particle pathway is not much larger than the tumor. As blood flow to the center of the tumor is usually severely restricted, more

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energetic decays offer improved therapy against larger tumors. Losing the metal during recoil (a problem with chelated but not fullerenes) may result in additional toxicity, particularly from the lanthanides which have biological half lives on the order of a decade. This is especially relevant as much recent work has been devoted to the lanthanide beta emitters  $^{90}\text{Y}$  and  $^{166}\text{Ho}$ , amongst others.

These studies will concentrate on producing, purifying, and derivatizing  $\text{Ho@C}_{82}$ . There are three main reasons for concentrating on  $\text{C}_{82}$  based compounds. First, for reasons that are not well understood, slightly more  $\text{C}_{82}$  lanthanide fullerenes are produced than other metal - containing fullerenes. Second, unlike other lanthanofullerenes  $\text{C}_{82}$  - based metallofullerenes are relatively stable with respect to oxidation in air and should be chemically similar to empty fullerenes (Suzuki 1993). Recently, the synthesis of derivatized metallofullerenes has confirmed this hypothesis (Suzuki et al. 1995 and Akasaka et al. 1995). Third, only  $\text{C}_{82}$  metallofullerenes are soluble in organic solvents such as toluene and can be extracted and purified using currently available chromatography methods (Section D.2).

**B.2 Fullerene Pharmacolgy** Research into the biological attributes of fullerenes as a class has only just begun. Several preliminary studies indicate that the fullerenes are well tolerated, are relatively nontoxic *in vivo*, and are certainly much less toxic than free lanthanide ions. The results of these studies are summarized *infra*.

Because of concerns of the potential carcinogenic effects of benzene and related polycyclic aromatic compounds (of which

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fullerenes, because of their  $\pi$ -conjugated surfaces might be considered similar), a study on the effect of topical fullerenes was undertaken by Nelson et al. (1993). They demonstrated a lack of carcinogenic effects from  $C_{80}$  and  $C_{70}$  after acute and subchronic applications to mice.

Tours and coworkers (W. A. Scrivens et al. 1994) produced  $^{14}C$  labelled  $C_{60}$  suspensions (particle size 0.30  $\mu m$  average diameter) in water and studied its uptake into human keratinocytes. The keratinocytes were exposed to the labelled fullerenes (32,000 dpm, 1.3  $\mu M$ ) and the uptake of the labelled  $C_{60}$  into the cells was monitored. After 6 hours approximately 50% of the applied radioactivity was taken up by the keratinocytes with no further increase noted for longer exposures. Washed cells continued to contain the suspended fullerenes over the next 11 hrs. Experiments to determine the effect of the  $C_{60}$  suspension on the proliferation rate of human keratinocytes and fibroblasts by monitoring of labelled thymidine uptake showed fullerenes had no effect on the rate of thymidine uptake.

The only systemic toxicity studies reported in the literature so far are those performed by R. F. Schinazi et al. (1994). In this study, a water soluble fullerene based HIV protease inhibitor was administered to groups of 6 mice at dosages of 15, 30, and 50 mg/kg. After a slight decline in weight in the treated and control groups (except for the untreated control group) all of the animals gained weight over the period of observation (see Figure 11) and none of the animals died. There was no statistical difference in the weight between the treated versus control groups and the authors concluded that their fullerene derivative is well

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tolerated up to a dose of at least 50 mkg. Continued monitoring showed none of the animals had died at 2 months after the start of the experiment.

5 The *in vivo* distribution of a particular water soluble  $^{14}\text{C}$  labeled fullerene administered to mice has also been determined (Yamago et al. 1995). After injection, the compound moved quickly to the liver and then was distributed to various other tissues. No acute toxicity was noted at  
10 does as high as 500 mg/kg, and all of the mice survived the one week test period. However, excretion of the compound was slow, with 90% being retained after one week. It also appears that the water solubilizing functional group, which contained the  $^{14}\text{C}$  label amid several ester linkages, was  
15 metabolized off of the fullerene. This suggests that the distribution and biological half life of fullerene derivatives may depend on the type of functional groups attached to the fullerene. Interestingly, in spite of the fact that it is a fairly large molecule, the fullerene  
20 derivative was able to cross the blood brain barrier, a fact that could be very important for future metallofullerene labelled pharmaceuticals.

The biodistribution in mice of hydroxylated lanthanide -  $\text{C}_{82}$  encapsulates is under current investigation. The results  
25 presented here are regarded as preliminary as the sample is still small. Studies continue under a NIH Phase I grant. The neutron irradiated samples, along with a  $^{166}\text{Ho}^{3+}$  control sample, were used to perform an  $\gamma$ -camera imaging study on  
30 four 300 g Sprague-Dawley rats. Two rats were injected intraperitoneally (IP) with 54 and 18  $\mu\text{Ci}$  of  $^{166}\text{Ho}$  activity from samples containing irradiated Ho-metallofulleroids. Two

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control studies were performed by IP administration of approximately 660  $\mu\text{Ci}$  of  $^{166}\text{Ho}^{3+}$  in a 1% sodium citrate buffer. The anesthetized rats were scanned side-by-side on a single stage with a  $\gamma$ -camera starting 1 hour after injection and periodically thereafter over the ensuing 48 hours.

The in-vivo imaging of the control rats showed rapid  $^{166}\text{Ho}^{3+}$  urinary clearance commencing, as soon as 1 hour post-injection. After 24 hours, essentially all  $^{166}\text{Ho}$  activity had been excreted from the controls. In contrast, the  $^{166}\text{Ho}$  activity from the Ho-metallofullerols produced a discernible image for up to 48 hours and showed an even distribution throughout the blood pool. Essentially no tissue localization was evident. After 48 hours, the  $^{166}\text{Ho}$  activity in the test rats became too low to image effectively ( $^{166}\text{Ho}$   $t_{1/2} = 26.8\text{hrs}$ ).

A second biodistribution study was performed on a single Balb/c mouse to provide a more detailed view of how the Ho-metallofullerol localized in-vivo. The results of this study are shown in Figure 12. Counting of the tissues shown was performed 1 hour after injection with the activities related back to the initial injected dose and corrected for the half-life decay. Additional  $^{166}\text{Ho}$  activity was also counted in the animal's cage, indicating that some clearance of the compound had occurred in the 1 hour before analysis.

Whereas previous fullerene biodistribution studies have demonstrated rapid liver uptake and retention, both of the present studies show that this is not the case for the metallofullerol samples. It appears that the type of

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derivation used to water-solubilize the fullerene is an important factor in determining its *in-vivo* localization. From a RIT point of view, these initial metallofullerol results are very encouraging. While the long-term biological fate of the presently studied Ho-metallo-fullerol is unclear because of the short  $^{166}\text{Ho}$  half-life, it seems rather certain that the observed biodistribution differs from that of simple lanthanide salts as well as underivatized fullerenes. Further testing with samples of higher activity and longer-lived radioisotopes will be necessary to fully resolve this question.

A very recent study reported by Dugan et al. in the 19 August 1997 *Proceeding of the National Academy of Sciences* reports that water-solubilized fullerenes "act as an effective anti-oxidant", sweeping up free radicals. Their studies, conducted on oxygen-and glucose-starved nerve cells which build up damaging free radicals, showed that the addition of a water-soluble fullerene derivative (derivatized by carboxylic acid groups) could cut cell death by 75%. Administration of the compound to mice bred to mimic familial amyotrophic lateral sclerosis (Lou Gehrig's disease) delayed the onset of symptoms by 10 days and increased their average 130 day life-span by 9 days. Dosing was accomplished by mini-osmotic pumps starting at 73 days of age and continuing until death. The administered dose corresponded to 15 mg/kg/day, and an equivalent dose for a typical 70 kg human (1.05g.) far more than that required for RIT. There appears to be no toxic effects from doses in this size range. The use of polyhydroxylated fullerols similar to those investigated in this project as non-toxic *in-vivo* free radical scavengers has also been demonstrated

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(Tsai et al. 1997 and Chueh et al. 1997). From the limited amount of studies that have been performed, it seems that the fullerene cage unit is non-toxic. Subject to further, more detailed investigations, it appears the future of fullerenes and metallofullerenes in medicine is quite promising.

**B. 3 Fullerene Antibodies** Excellent, high-affinity polyclonal antibodies to fullerenes have been prepared by essentially conventional methods. Anti-fullerene antibody formation proves that fullerene compounds are processed by the immune system in the same way as any other small molecule antigens. Specificity of the antibodies was confirmed by both binding and inhibition studies.

The anti-fullerene antibodies were produced by immunization of mice with a bovine thyroglobulin (TG) conjugate of a fullerene hemisuccinate F1 containing ca. 10-12 fullerenes per TG molecule. (Figure 13) After a primary immunization in Freund's adjuvant and two subsequent booster injections, the antibody response was confirmed by ELISA. The ELISA plate was coated with F1-rabbit serum albumin (RSA). Preimmune and post-immune sera were examined. Development was with horseradish peroxidase-labeled anti-mouse IgG, using o-phenylenediamine as substrate. A high titer of antibody was confirmed (Figure 4, first series of experiments).

Specificity of the antibodies was confirmed by double diffusion in agar (Figure 14). Lines of precipitation are seen in wells #1, 2, 3, 4, and 5, with a spur of #2 precipitate "pointing" to F1-BSA. This implies an additional



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reactive epitope in the F1-TG not present in its BSA conjugate. The overall interpretation of this experiment is that a population of C<sub>60</sub> - specific antibodies was produced, a subset of which also bound F3, a C<sub>70</sub> derivative.

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The specificity of the antibodies was confirmed by ELISA inhibition studies (Figure 15). Binding to F1 covalently lined to RSA was inhibited by F1-BSA, F1-RSA, F1-TG, F3-pentalysine, and F1-pentalysine. The pentalysine derivatives contained ca. 2.8 fullerenes per pentalysine molecule and were water soluble. This demonstrates that the antibody is specific for the fullerenes, not the conjugates. As the polyclonal Abfs also bind C<sub>70</sub>, a fullerene of intermediate size and somewhat more elongated shape, the likelihood of them accommodating the C<sub>82</sub> cage seems very high.

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Success at binding metallofullerenes to antibodies has profound implications for all techniques involving the transport of metals in vivo. While the fullerene keeps the metal completely contained, the Abf provides a handle for manipulation of the fullerene in vivo.

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**B.4 Radioimmunotherapy with Metallofullerenes** This work is aimed at RIT for several reasons. Primarily, the radioactive metals allow the most sensitive measurement techniques to be applied to tracking the development of the process, both in vivo and in vitro. Secondly, RIT has attracted much attention due to its great promise, but requires a technological breakthrough before it can be widely applied. A recent review (Wilder et al., 1996) summarizes the (mostly) very low response rates in clinical

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5 trials of RIT. Recent research has been towards shorter half-live radioisotopes, metabolizable linkages, and rapid clearing of the chelated radioisotope. These strategies are attempts at reducing the background dosage when the mAb does not rapidly find the tumor, compensating for its eventual separation from the radioisotope. If all metal atoms remain encapsulated over any length of time, as is true for metallofullerenes, the radionuclide is never separated from the mAb by leaving the chelate. Longer-lived radionuclides, such as  $^{177}\text{Lu}$ , suffer fewer decays while the mAb is locating the tumor, and therefore take best advantage of the metallofullerene delivery for one-step targeting (Schlom et al., 1991).

15 However, a single dosage of the fullerene-bispecific antibody may not be the best way to apply fullerenes to RIT. Some of the conventional problems have been mitigated by two- (Hnatowich et al., 1987) and three-step (Paganelli et al., 1991) targeting approaches. Use of metaallothone in 20 (~7 kDa) as a chelator is attractive because it is readily fused to other proteins by recombinant DNA technologies (Virzi, et al., 1995). However, its chelation ability was very poor in comparison to the more recent advanced synthetic chelating agents. A more common approach has been to link a good chelator (loss of ~1% of metal atoms per day) 25 to biotin (Vitamin H). Such assemblies have slightly lower molecular weights than fullerenes, indicating rapid circulation (and clearance) in vivo. Some problems have been encountered with cleavage of the chelator from biotin 30 (Rosebrough, 1993). In the three step program (Paganelli et al., 1991), a bispecific mAb, combining biotin with the antigen-specific component, is administered first. Avidin,

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which an association constant for biotin of order  $10^{15}$ , is added in the second step. In the final step, the biotin-chelate conjugate binds to the avidin. Even with this optimized (but arduous) administration program, only 0.012% of the injected dose was delivered to the tumor.

Similar multi-step approaches may be suitable for metallofullerene derivatives, depending on their pharmacokinetics. One possible strategy is to first administer a bispecific antibody that consists of an antigen-specific component and the Abf, followed by the metallofullerene. The available biodistribution studies of fullerenes indicate that, without stable functionalization to induce water solubility, they rapidly accumulate in the liver, from which clearance requires days. However, when water solubility is maintained, the mouse biodistribution indicates that fullerenes do not accumulate in any particular organ. As there are no natural receptors for fullerenes, they may exhibit very high in vivo selectivity for the Abf. Determination of binding constants, development of targeting strategies, and location of appropriate antigen-specific antibodies to link the Abf to are all appropriate tasks for Phase II research.

#### **D. Experimental Design and Methods**

The goal of the Phase I project is to demonstrate that endohedral metallofullerenes can be attached to fullerene antibodies. While these studies will isolate monoclonal antibodies for  $C_{62}$  with endohedral metal atoms, the work begins with the polyclonal mixture bioengineered in response to empty  $C_{60}$ . Four tasks consistent with specific aim have been formulated: 1) Synthesize holmium containing fullerenes;

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2) Purify the selected Holmium fullerene; 3) Derivatize the purified  $\text{Ho@C}_{82}$  to make it water soluble; 4) Bind the derivitized  $\text{Ho@C}_{82}$  to the fullerene antibodies. Figure 16 shows the flow of the research studies.

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**D.1 Task 1: Production of Holmium Metallofullerenes** The evaporation of graphite using a carbon arc in an inert atmosphere was the first successful approach for the production of macroscopic amounts of fullerene materials. This technique has also proven to be the method of choice for the production of macroscopic amounts of endohedral metallofullerenes as well. The graphite that is vaporized is doped with the desired metal in a form, such as  $\text{Ln}_2\text{O}_3$ , that is readily reduced to the neutral metal during vaporization. The metallo-fullerenes utilized in this project are likely to be produced by the conventional carbon arc method as described below.

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A current Phase II project is underway to produce bulk (kg) quantities of fullerenes and metallofullerenes using a continuous, combustion based process that can employ organometallic precursors. This process will substantially lower the cost of all types of fullerenes. Since its success is not guaranteed, described herein is a proven method for production fullerenes and metallofullerenes.

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A unique carbon arc reactor capable of both producing fullerenes and separating all the fullerenes from the raw soot has been designed. Because some fullerenes are radicals, all processing is performed under anaerobic conditions. The reactor is constructed primarily from quartz and serves to both vaporize the carbon rods and to perform

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an initial sublimation step. It is capable of generating several hundred milligrams of sublimed fullerene/metallofullerene mixture per 5" length of  $\frac{1}{8}$ " rod vaporized. The reactor is currently run in a single rod made by butting the  $\frac{1}{8}$ " rod to be vaporized against a larger  $\frac{1}{2}$ " diameter rod. The arc is run in DC mode with the polarity being reversed every few minutes to insure uniform evaporation. Multiple rods can be sequentially vaporized without venting the system by loading new rods into the reactor through the ball valve. Metal oxide doped carbon rods are produced by incipient wetness impregnation, a procedure developed at TDA and adequately described in the literature (Cagle et al., 1996). During the vaporization step, the fullerene collector is replaced by a seal to keep soot from going past the quartz baffle plate, and the tube furnace is removed to allow dissipation of the excess heat. Analysis of soot samples from different areas of the reactor after vaporizing one undoped graphite rod showed the yield of empty fullerenes (determined by quantitative HPLC) to be ~12%.

After evaporating several sets of graphite rods, the apparatus is pumped out to a vacuum of ~10 mtorr, and the electrodes are withdrawn. The furnace is replaced, and the quartz vessel is heated to 250 °C to allow any volatile impurities to be pumped away. The water cooled collector is now inserted through the gate valve, and the furnace is programmed to heat to 750 °C over several hours. The collector provides a water cooled surface area of 65 cm<sup>2</sup> upon which the fullerenes and metallofullerenes condense. Typical films, depending on the quantity of evaporated material, are on the order of 20-100  $\mu$ m thick. Depending

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upon the metal, approximately 200-1000 mg of sublimed material can be collected. From our current data, it is estimated that the yields collected by sublimation are equivalent to that collected by solvent extraction, but in contrast to solvent extraction, all of the small gap empty fullerenes and endohedral metallofullerenes produced (up to about 100 carbon atoms) readily sublime onto the collector. By performing the sublimation in two steps, at least 30% of the  $C_{60}$  and  $C_{70}$  can be removed in a first pass at 500 C, without losing significant amounts of  $Ln@C_{82}$ . This renders the higher temperature sublimate more concentrated in  $Ho@C_{82}$  crucial to its efficient purification (vida infra).

A mass spectrum (MS) of a typical sublimed sample (single step at high temperature) of Ho containing fullerenes is shown Figure 17. This spectra were obtained with TDA's laser desorption time-of-flight reflectron mass spectrometer. Metallofullerene samples were deposited on a stainless steel target disk from suspensions made by sonicating the metallofullerene solid in ethanol. Desorption and ionization were performed with 355 nm light from a Q-switched Nd-YAG laser. Peak intensities between the empty and metallofullerenes are not always quantitative, since metallofullerenes are easier to ionize than the empty fullerenes. In this case, empty fullerenes require three 355 nm photons to ionize while metallofullerenes require only two. The net result is an apparent enhancement of the metallofullerene signal (we estimate by a factor of two, based on measurements made using 157 nm light where 1 photon ionizes all of the fullerenes.) This makes  $Ho@C_{82}$  about as abundant as the higher empty fullerenes such as  $C_{84}$ .

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**D.2. Task 2: Purification of the Ho@C<sub>82</sub>**

Fullerenes from the concentrated sublimate will then be dissolved in xylene. Amongst lanthanide endohedral metallofullerenes, only the C<sub>82</sub> encapsule is soluble, which provides a rapid means of achieving purity amongst endohedral fullerene cage sizes. After filtering to remove the insolubles, the extract will be separated into its components using a semi-preparative high pressure liquid chromatography (HPLC) technique. Commercial columns with stationary phases have been developed specifically for separating fullerenes. A variety of these fullerene HPLC columns are available and it has been found that the Cosmosil PYE (2-(1-pyrenyl)ethyl) column is the best for Ln@C<sub>82</sub> separations. Much expertise in HPLC separation of Ln@C<sub>82</sub> has been acquired as the result of a previous study of Gd@C<sub>82</sub> as an MRI contrast agent. Thus, examples are cited from that procedure. The procedure for optimizing the collection of Ln@C<sub>82</sub> was developed during that work, and will be applied to the Ho@C<sub>82</sub> effort proposed here. It is not expected that the change from Gd to Ho will result in any significant behavioral differences in the HPLC of the endohedral metallofullerenes.

While previous work reported in the literature performed HPLC under aerobic conditions, (see for example Funasaka et al. 1995) these studies determined that anaerobic controls better preserved the fraction of Gd@C<sub>82</sub> in solution. (The hydroxylated, water soluble Gd@C<sub>82</sub>(OH)<sub>x</sub> derivative does not appear to be air sensitive.) Used was pure, degassed o-xylene as the mobile phase at a flow rate of 8ml/min, and all handling of the sample solutions was performed using anaerobic Schlenk line techniques. The fraction containing

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the  $\text{Gd@C}_{82}$  was identified using MS. The solubility of fullerenes in o-xylene is about three times that of toluene and this greatly increases the ratio of fullerenes in solution to those retained on the stationary phase. Therefore, the capacity or amount of fullerenes purified per injection was very large. Each injection contained 2 ml of saturated fullerene o-xylene solution (about 30 mg of fullerenes).

The  $\text{Gd@C}_{82}$  fraction was collected under Ar as it eluted from the column. The final solution, shown in Figure 18, was then stored under Ar until ready for derivatization. Because we started with a highly enriched fraction and handled it anaerobically, the purity of the sample is quite high (the integrated area is ~95%  $\text{Gd@C}_{82}$ , but as explained earlier, the absolute calibration is uncertain). The need for only a single, short HPLC step greatly facilitated separation of large quantities of  $\text{Gd@C}_{82}$ , and the production and purification process was then repeated to successfully produce approximately 25 mg of the material shown in Figure 11. Repeating this procedure for holmium fullerenes will collect an appropriate amount to prepare the water soluble derivative.

### D.3 Task 3: Producing the Water Soluble Holmium Fullerenes

The  $\text{Ho@C}_{82}$  will need to become water soluble in order to attach it to the fullerene antibodies. A wide variety of reactions have been shown to make  $\text{C}_{60}$  water soluble. Functionalization of the outside of the cage with about thirty hydroxyl groups has also been shown to be effective for endohedral metallofullerenes. One or more carboxylic acid groups have been linked to the fullerene in a variety



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of ways to induce water solubility. Inclusion in cyclodextrin and poly(vinylpyrrolidone) have also been successful. Polyhydroxylation, cyclodextrin inclusion, and complexation with poly(vinylpyrrolidone) are expected to alter the exterior of the cage beyond the recognition of the Abfs. Therefore, a carboxylic acid group is linked to the metallofullerene.

While only one other reaction of  $\text{Ln@C}_{82}$  has been demonstrated (besides polyhydroxylation, and that other one does not produce a water soluble derivative), the chemistry of the endohedral metallofullerenes is likely to be very similar to that of the empty fullerenes. The organic chemistry of empty fullerenes is a rapidly growing field, led by reactions of  $\text{C}_{60}$ . All chemical principles demonstrated on  $\text{C}_{60}$  also hold for larger fullerenes, although the isomeric mix of products varies according to the cage size and shape. The hemisuccinimide derivative used in the initial preparation of  $\text{C}_{60}$  antibodies was also demonstrated for  $\text{C}_{70}$ , and the same procedure will be followed for the  $\text{Ho@C}_{82}$ .

To prepare the empty fullerene derivatives (Lu, 1995), trans-trans-2,4 hexadien-1-ol was added to  $\text{C}_{60}$  in toluene under inert atmosphere. The mixture was then heated to 80 C overnight. After cooling, the solvent was removed. The residue was purified by flash column chromatography with toluene, followed by 20:1 toluene:ethyl acetate. That product was treated with dimethylaminopyridine and succinic anhydride under inert atmosphere in toluene:methylene chloride 1:1 solution. This mixture was warmed to 55 C for one day, followed by cooling and solvent removal. The residue was purified by flash column chromatography with

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methylene chloride followed by methylene chloride:ethanol >15:1. The product, a dark brown solid, is shown in Figure 19. These same steps will be followed for  $\text{Ho@C}_{82}$ .

5 While the procedure above creates a fullerene that remains water soluble only as long as the ester linkage remains intact, the F2 structure [see Fig. 13] results is a fullerene that is likely to remain water soluble under more adverse conditions. Its preparation is also a two step  
10 synthesis (Issacs and Diederich, 1993). This fullerene, or another ester-less derivative, may be used when maintaining solubility of fullerenes not bound to the Abf is desirable.

#### D.4 Task 4: Binding the derivitized $\text{Ho@C}_{82}$ to the fullerene

15 **antibodies** As for the preparation of the hemisuccinate derivative, the procedure for binding the  $\text{Ho@C}_{82}$  derivative to the Abf follow the procedure established for the empty fullerenes. The procedure for linking the  $\text{Ho@C}_{82}$  hemisuccinate to the RSA and pentalysine proceeds via  
20 reaction with N-hydroxysuccinimide and dicyclohexylcarbodiimide in pyridine. After two days at room temperature, crystals of dicyclohexylurea (a by-product of the reaction) need to be removed by centrifugation, leaving a solution of the fullerene N-hydroxysuccinimide  
25 ester (NHS). Half of the solution will be allowed to react with RSA at a ratio of 15:1  $\text{Ho@C}_{82}$ -NHS:RSA. The other half will be allowed to react with pentalysine at a ration of 5:1. This results in 10-12 metallofullerenes per molecule of RSA and 2.5 to 3 metallofullerenes per pentalysine.

30 Similarly, studies of its binding, and inhibition of its binding are carried out in precisely the same manner

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described in Section B.3. In the direct binding study, the ELISA plate will be coated with Ho@C<sub>82</sub>-RSA. In analogy to the previous experiments, also tested is inhibition of binding of antibody to C<sub>60</sub>-RSA by Ho@C<sub>82</sub>-RSA and Ho@C<sub>82</sub>-(lys)<sub>5</sub>.  
5 These tests confirm the binding of a metallofullerene to a fullerene antibody.

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What is claimed is:

1. An antibody which is specific for a fullerene or derivative thereof, wherein the fullerene is selected from the group consisting of a fullerene carbon compound having from 20 to 540 carbon atoms.
2. The antibody of claim 1, wherein the antibody is a monoclonal antibody.
3. The monoclonal antibody of claim 2, wherein the wherein the monoclonal antibody is a monospecific monoclonal antibody
4. The monoclonal antibody of claim 2, wherein the fullerene carbon compound or derivative thereof comprises a C60 fullerene.
5. The monoclonal antibody of claim 2, wherein the fullerene carbon compound or derivative thereof comprises a C70 fullerene.
6. The monoclonal antibody of claim 2, wherein the fullerene carbon compound or derivative thereof comprises a C76 fullerene.
7. The monoclonal antibody of claim 2, wherein the fullerene carbon compound or derivative thereof comprises a C78 fullerene.
8. The monoclonal antibody of claim 2, wherein the fullerene carbon compound or derivative thereof

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comprises a C84 fullerene.

9. The monoclonal antibody of claim 2, wherein the fullerene carbon compound or derivative thereof comprises a C240 fullerene.

10. An antibody which is specific for a single-walled fullerene nanotube, wherein the nanotube is an [n,m]-nanotube,  $n = 0 - 500$ ,  $m = 0 - 500$ , and  $n$  and  $m$  are the same or different.

11. The antibody of claim 10 which is a monoclonal antibody.

12. The monoclonal antibody of claim 10, wherein the antibody is a tip-specific antibody.

13. The monoclonal antibody of claim 10, wherein the antibody is a side-wall specific antibody.

14. An antibody which is specific for a multi-walled fullerene nanotube, wherein the nanotube is an [n,m]-nanotube,  $n = 0 - 500$ ,  $m = 0 - 500$ , and  $n$  and  $m$  are the same or different.

15. The antibody of claim 14 which is a monoclonal antibody.

16. The monoclonal antibody of claim 14, wherein the fullerene carbon compound or derivative thereof comprises a C78 fullerene.

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17. The monoclonal antibody of claim 14, wherein the fullerene carbon compound or derivative thereof comprises a C82 fullerene.
- 5 18. The monoclonal antibody of claim 14, wherein the fullerene carbon compound or derivative thereof comprises a C84 fullerene.
- 10 19. The monoclonal antibody of claim 14, wherein the fullerene carbon compound or derivative thereof comprises a C240 fullerene.
- 15 20. A nucleic acid molecule which encodes the monoclonal antibody of claim 1.
21. A nucleic acid molecule which encodes the monoclonal antibody of claim 10.
- 20 22. A nucleic acid molecule which encodes the monoclonal antibody of claim 14.
- 25 23. A hybridoma produced by the fusion of a mouse antibody-producing cell and a mouse myeloma, said hybridoma producing a monoclonal antibody which is specific for a fullerene.
- 30 24. A hybridoma produced by the fusion of a mouse antibody-producing cell and a mouse myeloma which is designated 1-10F-8A and deposited with the ATCC under Accession Number PTA-279, said hybridoma producing a monoclonal antibody which binds to fullerene C60.

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25. A mouse monoclonal antibody specific for a fullerene-C60 and produced by the mouse monoclonal antibody-producing hybridoma designated 1-10F-8A and deposited with the ATCC under Accession Number PTA-279.

5

26. The antibody of claim 1, wherein the antibody is a polyclonal antibody.

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27. The polyclonal antibody of claim 26, wherein the fullerene carbon compound or derivative thereof comprises a C60 fullerene.

15

28. The polyclonal antibody of claim 26, wherein the fullerene carbon compound or derivative thereof comprises a C70 fullerene.

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29. The polyclonal antibody of claim 26, wherein the fullerene carbon compound or derivative thereof comprises a C76 fullerene.

30. The polyclonal antibody of claim 26, wherein the fullerene carbon compound or derivative thereof comprises a C78 fullerene.

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31. The polyclonal antibody of claim 26, wherein the fullerene carbon compound or derivative thereof comprises a C84 fullerene.

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32. The polyclonal antibody of claim 26, wherein the fullerene carbon compound or derivative thereof comprises a C240 fullerene.

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33. A polyclonal antibody which binds to a single-walled fullerene nanotube.

34. The polyclonal antibody of claim 33, wherein the antibody is a tip-specific antibody.

35. The polyclonal antibody of claim 33, wherein the antibody is a side-wall specific antibody.

36. A polyclonal antibody which binds to a multi-walled fullerene nanotubes.

37. An antibody specific for a fullerene, wherein the fullerene is selected from the group consisting of a fullerene carbon compound or derivative thereof comprising from 20 to 540 carbon atoms, wherein a radioactive material is encapsulated in the fullerene.

38. A method of determining a serum concentration of a fullerene in a subject which comprises:

a) determining an amount of antibody which binds to the fullerene in the absence of serum;

b) incubating a serum sample from a subject with an antibody which binds to the fullerene to form an antibody-fullerene complex;

c) determining the amount of antibody which binds to the fullerene in the presence of serum by detecting the amount of fullerene complex;



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d) comparing the amount determined in step (c) with the amount determined in step (a), hereby determining the serum concentration of the fullerene in the subject.

- 5        39. The method of claim 38 wherein the amount of antibody which binds to the fullerene in the absence of serum is determined for differing amounts of fullerene.
- 10       40. The method of claim 38, wherein the detection of steps (a) and (c) is performed with a second antibody which binds to the antibody-fullerene complex, said second antibody being detectably labeled.
- 15       41. The method of claim 40, wherein the detectable label of the second antibody is selected from the group consisting of a radioactive isotope, enzyme, dye, biotin, a fluorescent label or a chemiluminescent label.
- 20       42. The method of claim 40, wherein the second antibody of step (c) is either a monoclonal antibody or a polyclonal antibody.
- 25       43. The method of claim 41, wherein the second antibody is detectably labeled.
- 30       44. The method of claim 43, wherein the detectable label of the second antibody is selected from the group consisting of a radioactive isotope, enzyme, dye, biotin, a fluorescent label or a chemiluminescent label.

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45. A method of purifying a fullerene from a sample which comprises:

5 a) preparing an affinity chromatography column to which are bound antibodies which bind to the fullerene;

10 b) adding a sample to the affinity chromatography column so as to allow the sample to flow through the column, thereby permitting the fullerene to bind to the antibodies, thereby forming a fullerene-antibody complex on the column; and

15 c) separating the fullerenes from the antibody-fullerene complex of step (b) by altering the pH,

thereby purifying the fullerene from the sample.

20 46. The method of claim 45, wherein the pH is lowered to approximately pH 3.0.

47. The method of claim 45, wherein the pH is raised to between approximately pH 9.0-10.0.

25 48. A method of preparing a nanoscale device which comprises manipulating a single-walled fullerene nanotube or nanotubes with the antibody of claim 10 to assemble electronic or chemical components of the nanoscale device.

30 49. A method of preparing a nanoscale device which comprises manipulating a multi-walled fullerene nanotube or nanotubes with the antibody of claim 14 to

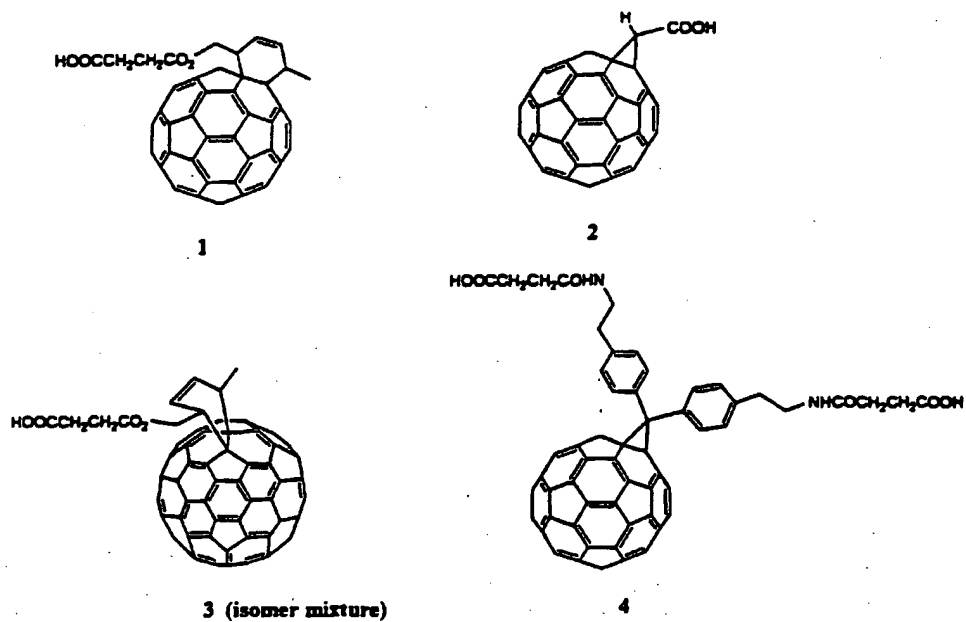
-106-

assemble electronic or chemical components of the nanoscale device.

- 5 50. The method of claim 48 or 49, wherein the nanoscale device is selected from the group consisting of a nanoscale optics device, a nanoscale electronic device, and a nanoscale biosensor device.

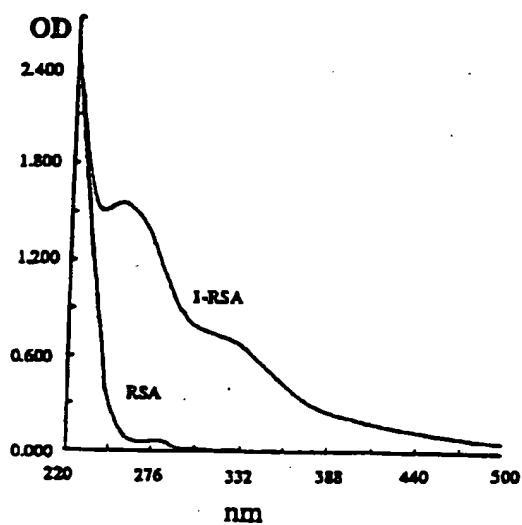
1/23

FIG. 1



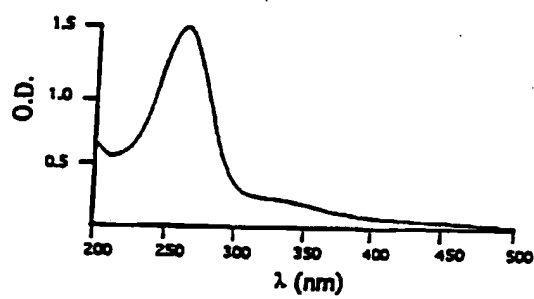
2/23

FIG. 2



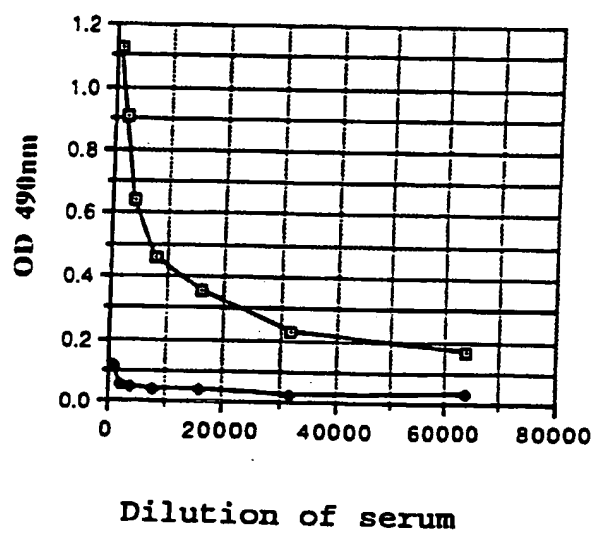
3/23

FIG. 3



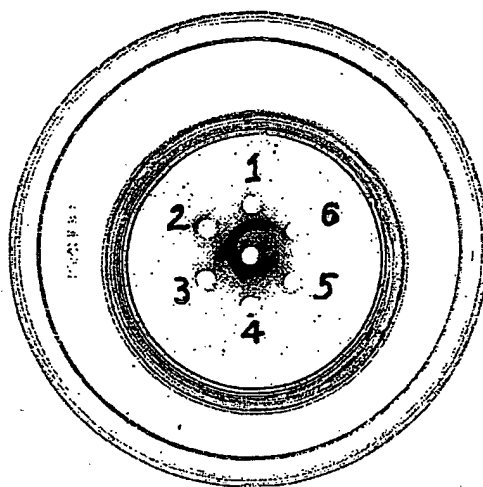
4/23

FIG. 4



5/23

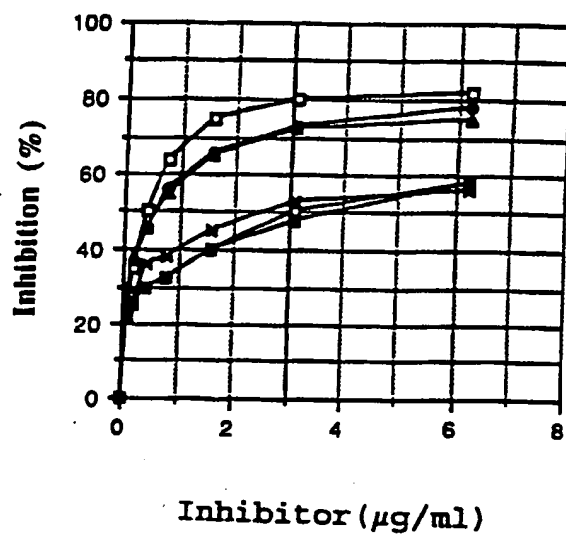
FIG. 5



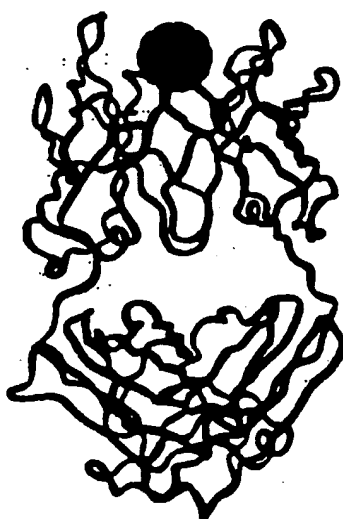
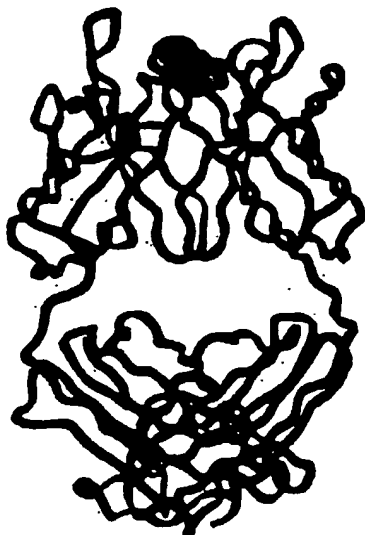


6/23

FIG. 6

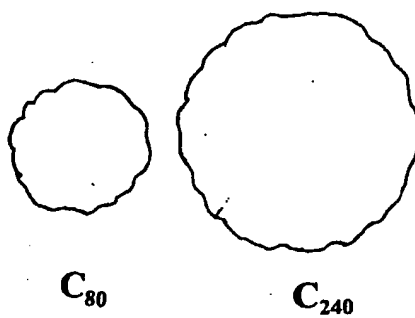


7/23  
FIG. 7



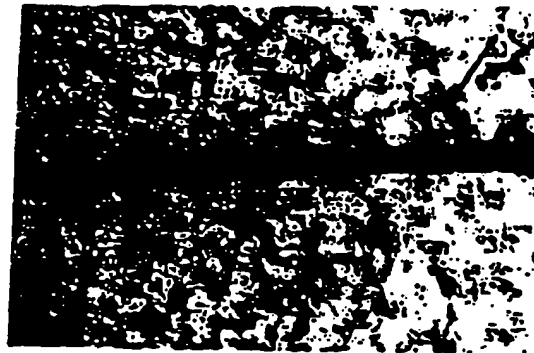
8/23

FIG. 8



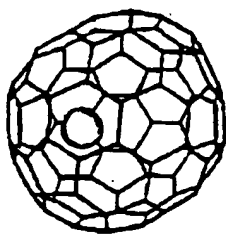
9/23

FIG. 9



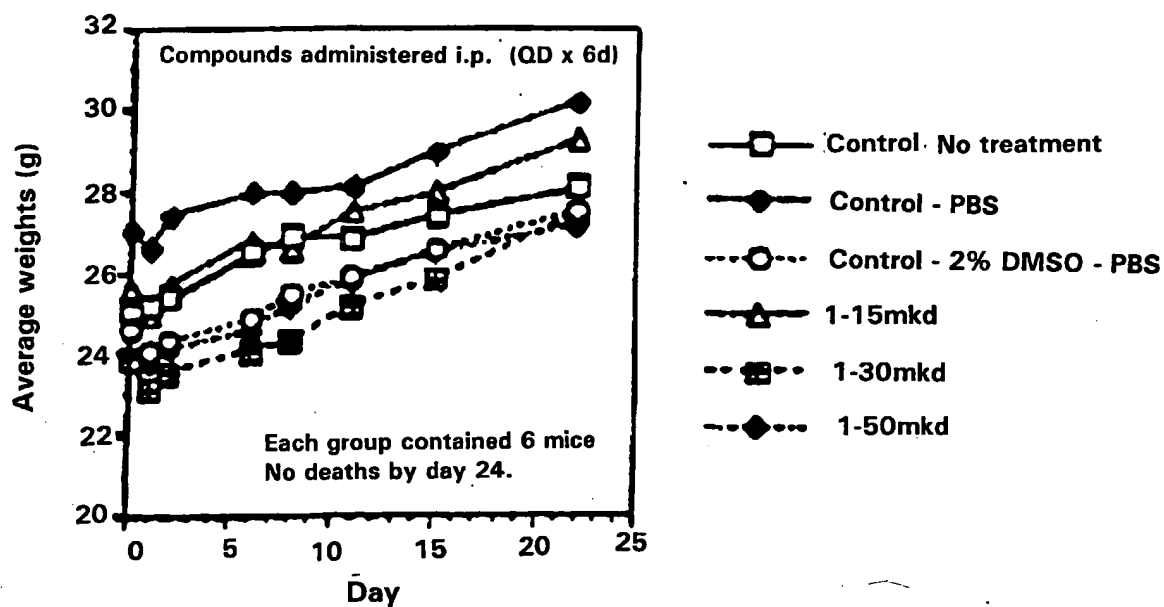
10/23

FIG. 10



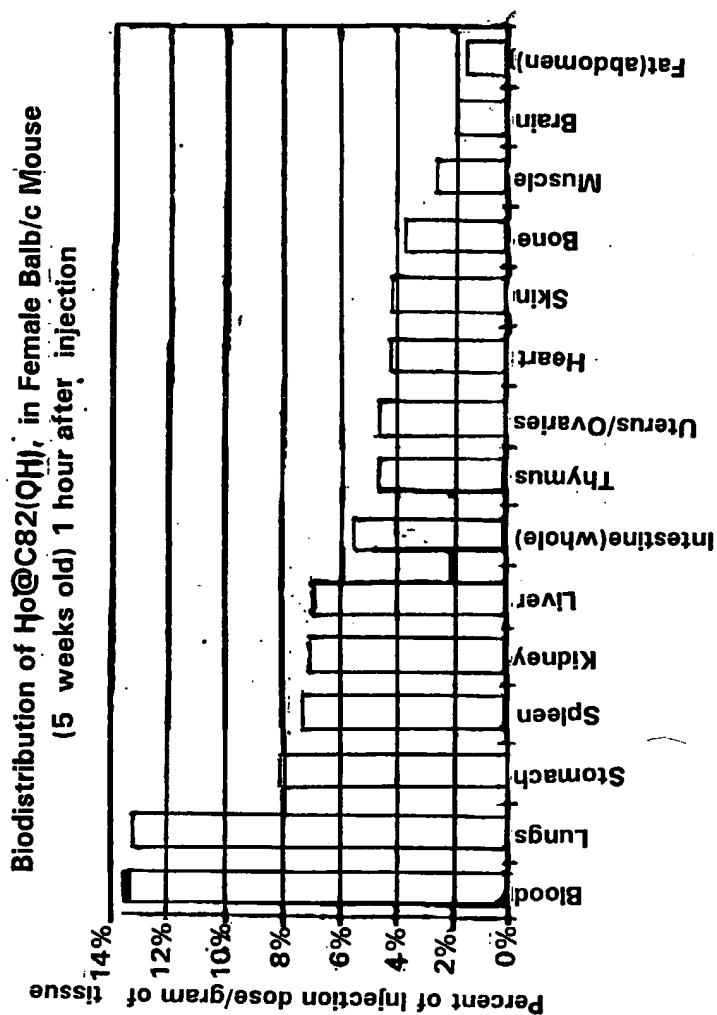
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FIG. 11



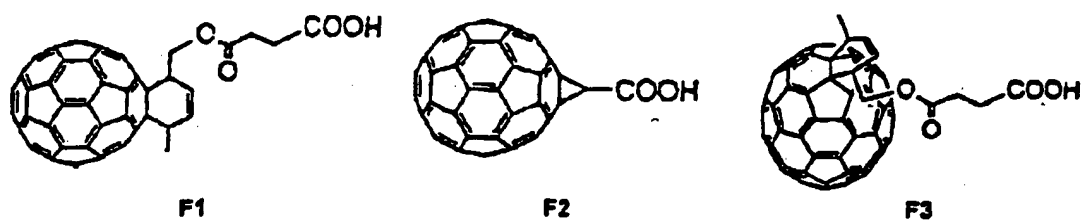
12/23

FIG. 12



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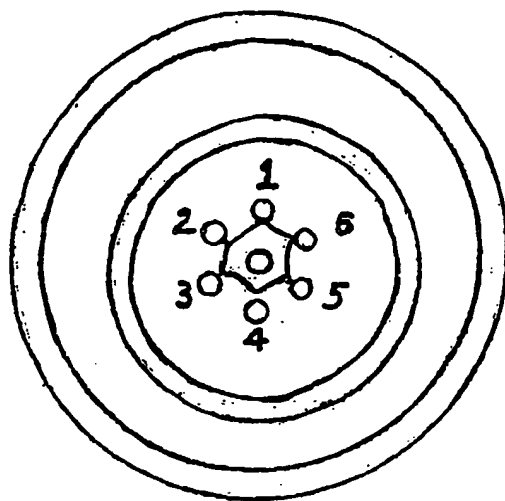
FIG. 13





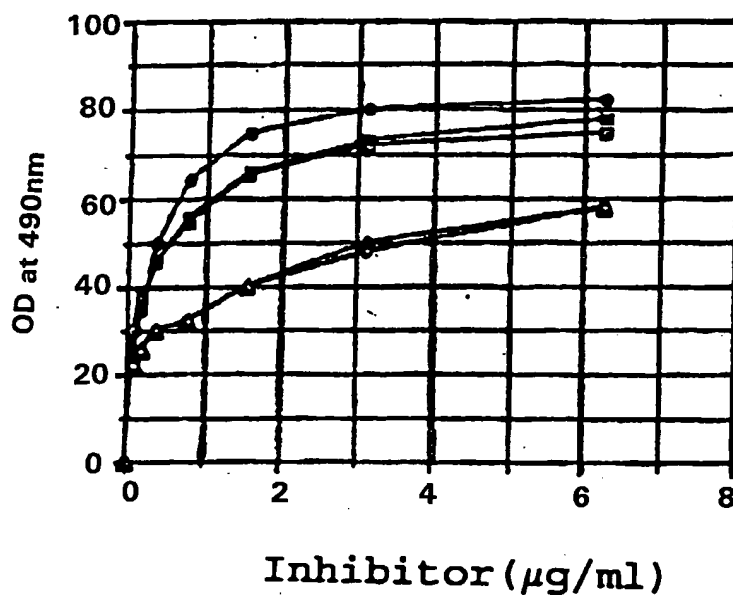
14/23

FIG. 14



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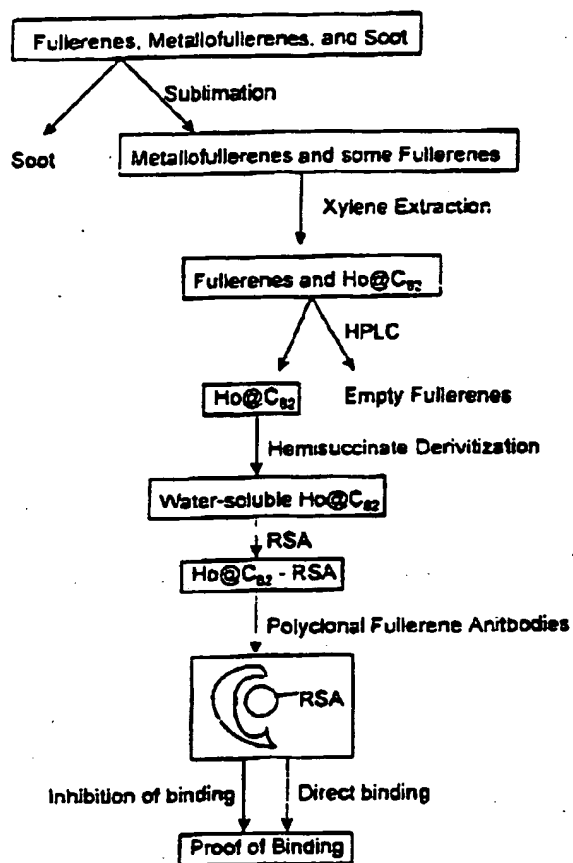
FIG. 15



- F-1-BSA
- ▲— F-1-(lys)5
- F-1-RSA
- ◆— F-1-TG
- ◇— F-3-(lys)5

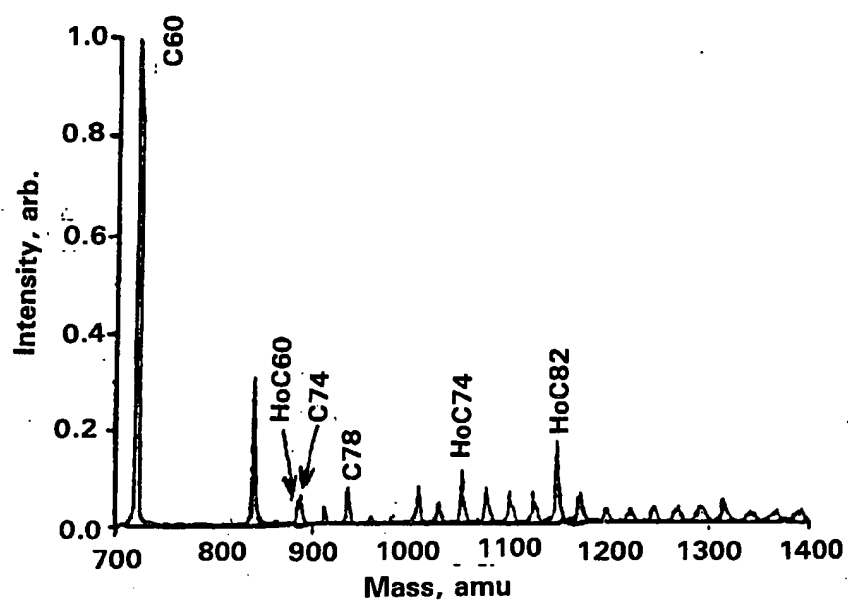
16/23

FIG. 16



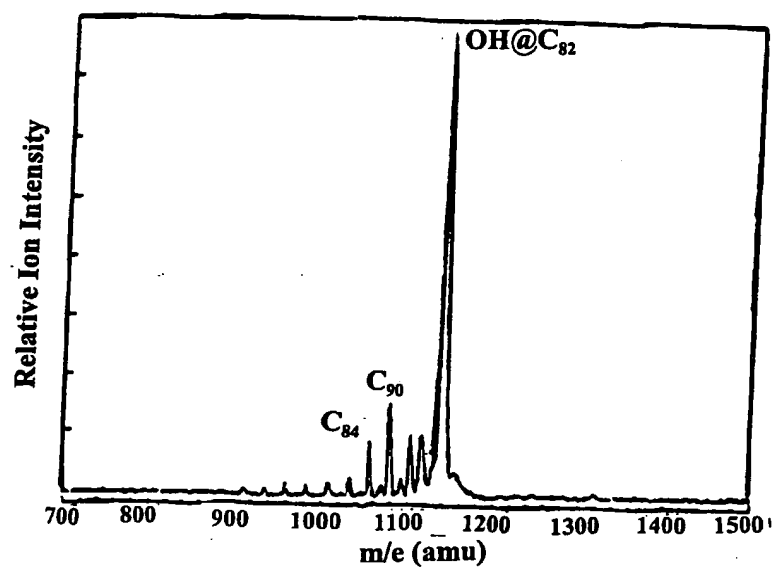
17/23

FIG. 17



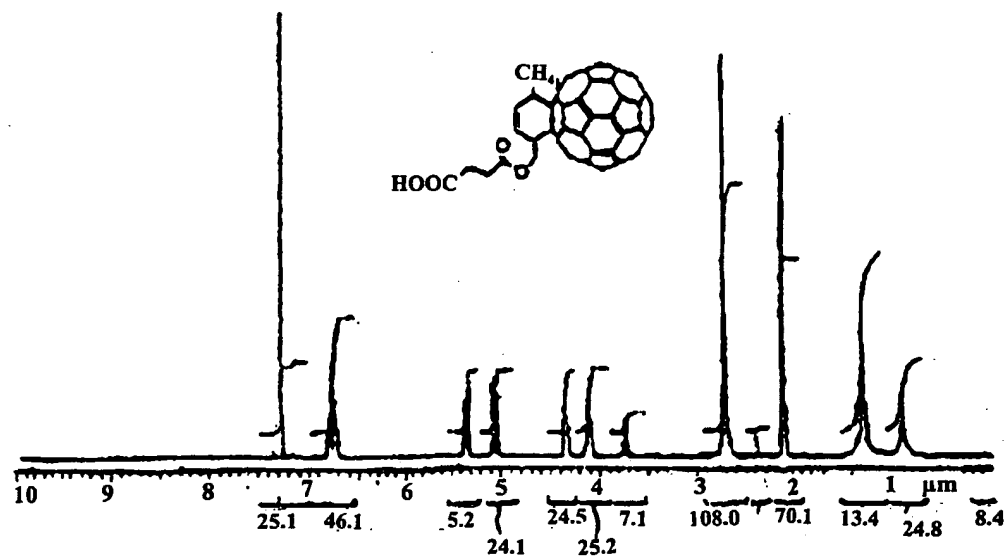
18/23

FIG. 18



19/23

Fig. 19



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FIG. 20

## H2-R -&gt; 1-phase Translation

DNA sequence 398 b.p. ATGGGATGCAGC ... TGTCTCTGCAGC linear

```

1/1                               31/11
ATG GGA TGC AGC TGG GGC ATG CTC TTC CTC CTG TCA ATA ACT GCA GGT GTC CAT TGC CAG
M  G  C  S  W  G  M  L  F  L  L  S  I  T  A  G  V  H  C  Q
61/21                               91/31
GTC CAC CTA CAA CAA TCT GGA CCT GAG CTG GTG AGG CCT GGG GCC TCA GTG AAG ATT TCC
V  H  L  Q  Q  S  G  P  E  L  V  R  P  G  A  S  V  K  I  S
121/41                               151/51
TGC AAA ACT TCT GGC TAC GTA TTC AGT AGT TCT TGG ATG AAC TGG GTG AAA CAG AGG OCT
C  K  T  S  G  Y  V  F  S  S  S  W  M  N  W  V  K  Q  R  P
181/61                               211/71
GGA CAG GGT CTT AAG TGG ATT GGA CGA ATT TAT CCT GGA AAT GGA AAT ACT AAT TAC AAT
G  Q  G  L  K  W  I  G  R  I  Y  P  G  N  G  N  T  N  Y  N
241/81                               271/91
GAG AAA TTC AAG GGC AAG GCC ACA CTG ACT GCA GAC AAA TCC TCC AAC ACA GCC TAC ATG
E  K  F  K  G  K  A  T  L  T  A  D  K  S  S  N  T  A  Y  M
301/101                               331/111
CAG CTC AGC AGC CTG ACC TCT GTG GAC TCT GCG GTC TAT TTC TGT GCA ACA TCC TCG GCT
Q  L  S  S  L  T  S  V  D  S  A  V  Y  F  C  A  T  S  S  A
361/121                               391/131
TAC TGG GGC CAA GGG ACT CTG CTC ACT GTC TCT GCA GC
Y  W  G  Q  G  T  L  L  T  V  S  A

```

21/23

FIG. 21

## L16-F -&gt; 1-phase Translation

DNA sequence 327 b.p. GATATCCAGATG ... ATAAAACGTAAG linear

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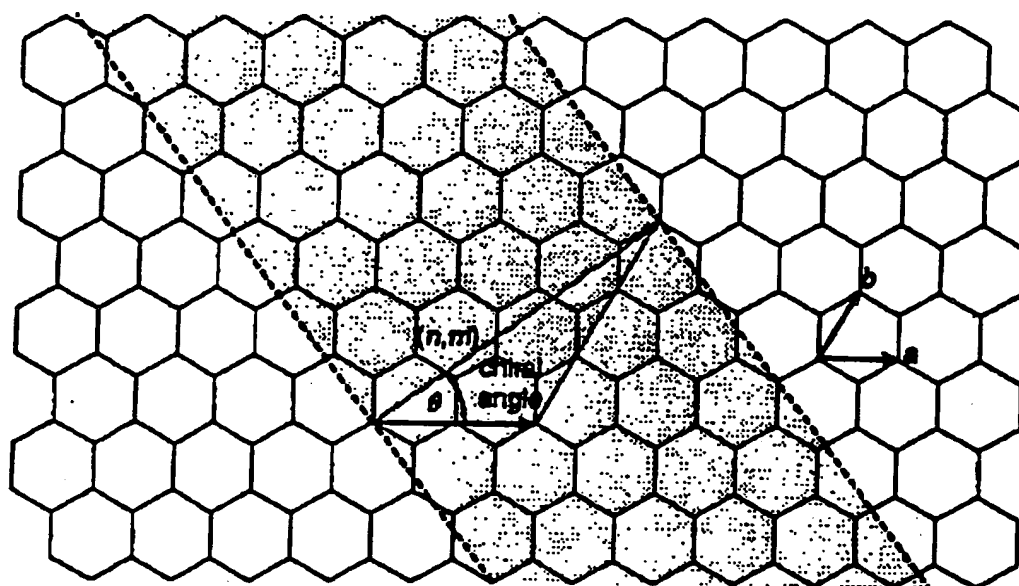
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D I Q M T Q T T S S L S A S L G D R V T
61/21
TTC AGT TCC AGT GCA AGT CAG GAT ATT AAC AAT TAT TTA AAC TGG TAT CAG CAG AAA CCA
F S C S A S Q D I N N Y L N W Y Q Q K P
121/41
GAT GCA ACT ATT AAA CTC CTA ATC TAT TAC ACA TCA AGT TTA CGC TCA GGA GTC CCA TCA
D G T I K L L I Y Y T S S L R S G V P S
181/61
AGG TTC AGT GGT AGT GCG TCT GGG ACA GAT TAT TCT CTC ACC ATC AAC AAC CTG GAA CCT
R F S G S G S G T D Y S L T I N N L E P
241/81
GAA GAT ATT GCC ACT TAT TTT TGT CAG CAG TAT AGT AGG CTT CCG TTC ACG TTC GGC TCG
E D I A T Y F C Q Q Y S R L P F T F G S
301/101
GGG ACA AAG TTG GAA ATA AAA CGT AAG
G T K L E I K R K

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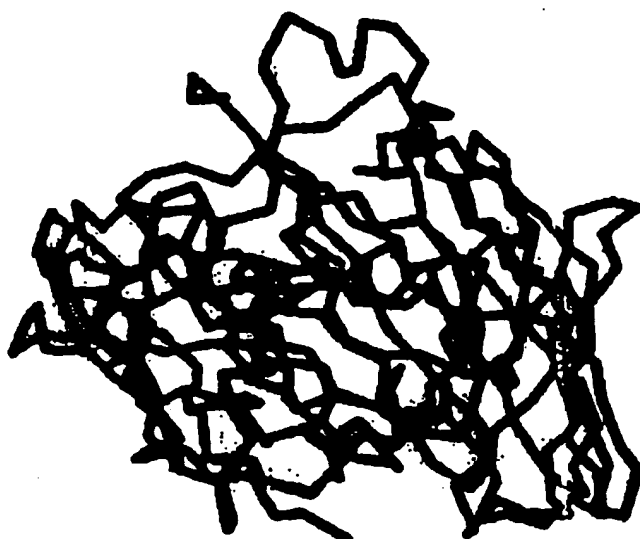
22/23

FIG. 22



23/23

FIG. 23



## SEQUENCE LISTING

&lt;110&gt; The Trustees of Columbia University in the City of

&lt;120&gt; Antibodies Specific for Fullerenes

&lt;130&gt; 54182-pct/jpw/emw

&lt;140&gt; NOT YET KNOWN

&lt;141&gt; 2000-08-29

&lt;150&gt; 09/386,658

&lt;151&gt; 1999-08-31

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&lt;170&gt; PatentIn Ver. 2.1

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&lt;211&gt; 398

&lt;212&gt; DNA

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&lt;220&gt;

&lt;221&gt; CDS

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1 5 10 15	
gtc cat tgc cag gtc cac cta caa caa tct gga cct gag ctg gtg agg	96
Val His Cys Gln Val His Leu Gln Gln Ser Gly Pro Glu Leu Val Arg	
20 25 30	
cct ggg gcc tca gtg aag att tcc tgc aaa act tct ggc tac gta ttc	144
Pro Gly Ala Ser Val Lys Ile Ser Cys Lys Thr Ser Gly Tyr Val Phe	
35 40 45	
agt agt tct tgg atg aac tgg gtg aaa cag agg cct gga cag ggt ctt	192
Ser Ser Ser Trp Met Asn Trp Val Lys Gln Arg Pro Gly Gln Gly Leu	
50 55 60	
aag tgg att gga cga att tat cct gga aat gga aat act aat tac aat	240
Lys Trp Ile Gly Arg Ile Tyr Pro Glv Asn Gly Asn Thr Asn Tyr Asn	
65 70 75 80	

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 Glu Lys Phe Lys Gly Lys Ala Thr Leu Thr Ala Asp Lys Ser Ser Asn  
                     85                    90                    95

aca gcc tac atg cag ctc agc agc ctg acc tct gtg gac tct gcg gtc 336  
 Thr Ala Tyr Met Gln Leu Ser Ser Leu Thr Ser Val Asp Ser Ala Val  
                     100                    105                    110

tat ttc tgt gca aca tcc tcg gct tac tgg ggc caa ggg act ctg ctc 384  
 Tyr Phe Cys Ala Thr Ser Ser Ala Tyr Trp Gly Gln Gly Thr Leu Leu  
                     115                    120                    125

act gtc tct gca gc 398  
 Thr Val Ser Ala  
                     130

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<212> PRT

<213> Mus musculus

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           1                    5                    10                    15

Val His Cys Gln Val His Leu Gln Gln Ser Gly Pro Glu Leu Val Arg  
                     20                    25                    30

Pro Gly Ala Ser Val Lys Ile Ser Cys Lys Thr Ser Gly Tyr Val Phe  
                     35                    40                    45

Ser Ser Ser Trp Met Asn Trp Val Lys Gln Arg Pro Gly Gln Gly Leu  
           50                    55                    60

Lys Trp Ile Gly Arg Ile Tyr Pro Gly Asn Gly Asn Thr Asn Tyr Asn  
           65                    70                    75                    80

Glu Lys Phe Lys Gly Lys Ala Thr Leu Thr Ala Asp Lys Ser Ser Asn  
                     85                    90                    95

Thr Ala Tyr Met Gln Leu Ser Ser Leu Thr Ser Val Asp Ser Ala Val  
                     100                    105                    110

Tyr Phe Cys Ala Thr Ser Ser Ala Tyr Trp Gly Gln Gly Thr Leu Leu  
                     115                    120                    125

Thr Val Ser Ala

130

&lt;210&gt; 3

&lt;211&gt; 327

&lt;212&gt; DNA

&lt;213&gt; Mus musculus

&lt;220&gt;

&lt;221&gt; CDS

&lt;222&gt; (1)..(327)

&lt;400&gt; 3

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Asp Ile Gln Met Thr Gln Thr Thr Ser Ser Leu Ser Ala Ser Leu Gly	
1 5 10 15	

gac aga gtc acc ttc agt tgc agt gca agt cag gat att aac aat tat	96
Asp Arg Val Thr Phe Ser Cys Ser Ala Ser Gln Asp Ile Asn Asn Tyr	
20 25 30	

tta aac tgg tat cag cag aaa cca gat gga act att aaa ctc cta atc	144
Leu Asn Trp Tyr Gln Gln Lys Pro Asp Gly Thr Ile Lys Leu Leu Ile	
35 40 45	

tat tac aca tca agt tta cgc tca gga gtc cca tca agg ttc agt ggt	192
Tyr Tyr Thr Ser Ser Leu Arg Ser Gly Val Pro Ser Arg Phe Ser Gly	
50 55 60	

agt ggg tct ggg aca gat tat tct ctc acc atc aac aac ctg gaa cct	240
Ser Gly Ser Gly Thr Asp Tyr Ser Leu Thr Ile Asn Asn Leu Glu Pro	
65 70 75 80	

gaa gat att gcc act tat ttt tgt cag cag tat agt agg ctt ccg ttc	288
Glu Asp Ile Ala Thr Tyr Phe Cys Gln Gln Tyr Ser Arg Leu Pro Phe	
85 90 95	

acg ttc ggc tcg ggg aca aag ttg gaa ata aaa cgt aag	327
Thr Phe Gly Ser Gly Thr Lys Leu Glu Ile Lys Arg Lys	
100 105	

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&lt;211&gt; 109

&lt;212&gt; PRT

&lt;213&gt; Mus musculus

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20 25 30

Leu Asn Trp Tyr Gln Gln Lys Pro Asp Gly Thr Ile Lys Leu Leu Ile  
35 40 45

Tyr Tyr Thr Ser Ser Leu Arg Ser Gly Val Pro Ser Arg Phe Ser Gly  
50 55 60

Ser Gly Ser Gly Thr Asp Tyr Ser Leu Thr Ile Asn Asn Leu Glu Pro  
65 70 75 80

Glu Asp Ile Ala Thr Tyr Phe Cys Gln Gln Tyr Ser Arg Leu Pro Phe  
85 90 95

Thr Phe Gly Ser Gly Thr Lys Leu Glu Ile Lys Arg Lys  
100 105

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US00/23629

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(7) :C07H 21/04; C07K 16/44; G01N 33/53, 33/577

US CL :Please See Extra Sheet

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

U.S. : Please See Extra Sheet.

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EAST, DIALOG

search terms: fullerene, buckminsterfullerene, buckyball, antibod?

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	CHEN et al. Antigenicity of Fullerenes: Antibodies Specific for Fullerenes and Their Characteristics. Proceedings of the National Academy of Sciences USA. September 1998, Vol. 95, pages 10809-10813, see entire document.	1-50
Y	CHEN et al. Antibodies to Fullerenes and Their Properties. FASEB Journal. 20 March 1998, Vol. 12, No. 5 (2 Suppl.), page A887, the Abstract No. 5135, see entire document.	1-50
A	IZHAKY et al. What Else Can the Immune System Recognize? Proceedings of the National Academy of Sciences USA. September 1998, Vol. 95, pages 11509-11510, see entire document.	1-50

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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*O* document referring to an oral disclosure, use, exhibition or other means		
*P* document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

11 OCTOBER 2000

Date of mailing of the international search report

27 NOV 2000

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Washington, D.C. 20231

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Authorized officer

JAMES L. GRUN, PH.D.

Telephone No. (703) 308-0196

**INTERNATIONAL SEARCH REPORT****International application No.**  
**PCT/US00/23629**

<b>C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT</b>		
<b>Category*</b>	<b>Citation of document, with indication, where appropriate, of the relevant passages</b>	<b>Relevant to claim No.</b>
<b>A</b>	<b>JENSEN et al. Biological Applications of Fullerenes. Bioorganic and Medicinal Chemistry. 1996, Vol. 4, No. 6, pages 767-779, see entire document.</b>	<b>1-50</b>



## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US00/23629

### A. CLASSIFICATION OF SUBJECT MATTER:

US CL :

435/6, 7.1, 7.5, 7.92, 7.93, 7.95, 70.21, 172.2, 326, 345; 530/ 387.1, 388.9, 389.1, 389.8, 413; 536/23.53

### B. FIELDS SEARCHED

Minimum documentation searched

Classification System: U.S.

435/6, 7.1, 7.5, 7.92, 7.93, 7.95, 70.21, 172.2, 326, 345; 436/518, 536, 547, 548; 530/ 387.1, 388.9, 389.1, 389.8, 413, 807; 536/23.53; 935/104, 108, 110

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